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Can We Feed the World in 2050?

A Scoping Paper to Assess the Evidence

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Abstract

Alarms sounded following the 2007-8 food price increases regarding our ability to feed the world in 2050. Some said we need to double food production. Other estimates projected a 60% increase in agricultural production to meet rising population and changing diets. This paper looks behind those estimates to assess many of the economic models that have generated the most widely cited projections. A range of models are assessed, a typology of modeling is offered, and the strengths and limitations of different estimates are offered. Notable weaknesses include underestimates of the impacts of biofuels expansion and the uncertainties related to climate change and its impacts on agricultural production. We conclude with a set of recommendations regarding future modeling and the need to provide policy-makers with useful scenario analysis to help them gauge the impacts of policy alternatives.

Keywords: agriculture, food policy, economic modeling, climate change, biofuels, hunger.

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Introduction

> *"Model outputs should not be misinterpreted as forecasts with well-defined confidence intervals. Rather they are meant to provide quantified insights about the complex interactions in a highly interdependent system and the potential general size order of effects, which cannot be obtained by qualitative and theoretical reasoning alone."*[2]

Malthus was right! At least, that is what one might conclude from the alarms that sounded with the doubling of global agricultural commodities prices in 2008. The common reference point was 2050, when the global population is expected to surpass 9 billion. Would the food needs of that population finally outstrip societies' ability to grow it, as Thomas Malthus (1798) warned in his famous 1798 treatise, *An essay on the principle of population*? His predictions, from what amounted to one of the first global modeling studies on the world's ability to feed its growing population, have been widely discredited. But resource constraints, exacerbated by uncertainties over climate change, have revived questions about the ability of societies and the planet to feed our growing population.

The 2008 price spikes were the trigger, and warnings came from far and wide. The heads of the UN's Food and Agriculture Organization (FAO) and World Food Program (WFP) called on the world to double food production by 2050 to meet rising demand, not just from a growing population but one that is expected to consume more meat, and from the rapidly growing demand for bioenergy crops (World Food Program 2009).

"With almost 80 million more people to feed each year, agriculture can't keep up with the escalating food demand," warned Frank Rijsberman, head of the Consultative Group on International Agricultural Research (CGIAR). "FAO estimates that we have to double food production by 2050 to feed the expected 9 billion people, knowing that one billion people are already going to bed hungry every day." (Rijsberman 2012)

In fact, the FAO had not called for a doubling of food production by 2050, at least its experienced team of agricultural modelers hadn't. The agency's models had

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[2] Reilly, Michael and Dirk Willenbockel (2010). "Managing uncertainty: a review of food system scenario analysis and modelling." Philosophical Transactions of the Royal Society **365**: 3049-3063. Page 2053.

suggested, in fact, that we needed to increase agricultural production – not just food production – by 70% from 2005/07- 2050 (FAO 2009). A 2012 update of those estimates brought the figure down to 60% for the same period (for explanations of the updated estimate see (Alexandratos and Bruinsma 2012).

Still, the 100% and 70% figures lived on in public pronouncements on the food price crisis. Some came from business interests with much to gain. Monsanto still states that we "need to double the amount of food we currently produce." (Monsanto 2013) Respected author Gordon Conway (2012), in his recent book, *One Billion Hungry: Can We Feed the World?,* echoes the widely circulated but poorly sourced need for a 100% increase in food production by 2050. Some of the warnings come from well-intentioned public officials trying to provoke needed action on agricultural investment and development. As late as 2011, UN agencies were warning of needed increases of "70 to 100 percent" (DESA 2011).

As the FAO's modelers note, the 70% estimate "seems to have assumed a life of its own," becoming the most widely quoted estimate. At least the FAO's own officials now cite the more updated figure, saying before the 2012 Rio +20 summit, "we need to improve people's access to food in their communities, increase production by 60 per cent by 2050, drastically reduce huge losses and waste of food and manage our natural resources sustainably, so that it flourishes for future generations" (Nwanze, Graziano da Silva et al. 2012).

The purpose of this paper is to examine the basis for the various claims regarding future needs from agriculture and assess the implications. Indeed, a small industry has sprung up around the question of feeding the world in 2050, and the studies diverge widely in their assessments. The estimates matter, precisely because they drive both public discourse and public policy. Are we facing a Malthusian future of food scarcity, or perhaps a "limits to growth" scenario in which the carrying capacity of the planet reaches exhaustion?

Perhaps more important, how well do these estimates of global food demand and supply adequately incorporate the uncertainties occasioned by changing economic and environmental trends, from climate change to biofuels expansion, from slowing agricultural yields to rising meat demand from a growing global middle class? Modeling often relies on "business-as-usual" scenarios that treat current practices as inevitable. Yet climate change, which is characterized by a daunting array of uncertainties, will generate impacts on future agricultural production even if steps are taken now to slow emissions of greenhouse gases.

Finally, does the modeling offer useful guidance to policy-makers on the drivers of unsustainably high agricultural prices and on the public policies that can address them, including the sustainable use of resources?

This review represents more of a user's guide to this modeling than an assessment of modeling itself, or of the range and types of models used in such research (see Reilly and Willenbockel 2010 for a good overview, pp 3051-3). We begin by tracing the origins of the main assertions, explaining the reliability and limitations of those efforts. We then step back to examine the difficulties inherent in such long-range modeling, then identify some useful typologies to integrate a broader range of 2050 projections. In the next section, we look at some of the scenario modeling that has been done on key drivers of 2050 results, specifically agricultural productivity, biofuels expansion, and climate change. We then touch briefly on the use of biophysical models to assess future resource use, particularly land and water. Next, we examine some of the normative modeling that has been developed to address broader scenarios that encompass multi-dimensional changes in societal paths. We conclude with some observations on the strengths and limitations of the 2050 modeling to date and suggest areas in which it can provide the most useful contributions to decision-making.

Background – Review of models and their estimates

The most widely quoted figures come from the FAO's efforts over time to gauge food demands in the future. Their estimates immediately after the 2007-8 food price spikes, suggesting the need to double food production from 2005/07- by 2050, served as the basis for international alarms about our ability to feed the world. While that figure is still cited by policy-makers, the FAO's later estimate of a 70% increase in agricultural production seems to have taken hold as the most commonly cited figure. The FAO's more recent update in June 2012, which lowered the figure to 60%, is recognized as the best reliable estimate by the FAO and food policy-makers, though the 70% figure remains widely cited in government circles and in the media.

How reliable are these estimates? There are a number of misconceptions about the nature of such modeling, and they have implications for any effort to assess not just what is likely to happen but also what could happen under different environmental or policy scenarios. First, the FAO is very clear in its presentations that it is not answering the question, "How can we feed the world in 2050?" It is answering the much more straightforward question: Will world production increase enough to meet projected demand?

Their answer is yes. And the FAO estimates should indeed offer some reassurance – with very important caveats – to those who would sound alarms over our ability to produce enough food to feed the population in 2050. Why is this reassuring?

1. Much of the data has been updated to more recent base years (2005-7) and the modelers have incorporated recent and improved estimates of food demands, land and water resources, etc. In fact, the shift from 70% to 60% reflects less a change in the estimated demand than it does an updated (and higher) figure reflecting actual production in the 2005-7 base year period.
2. It is based on widely accepted – but still uncertain– population growth figures (9.15 billion in 2050[3]), well-grounded estimates of economic growth (average

[3] Population growth rates are anticipated to vary widely depending on the country. Alexandratos et al (2012) notes that the majority of countries whose population growth is expected to be fast in the future are those showing inadequate food consumption and high levels of undernourishment, mostly in sub-Saharan Africa.

global GDP growth of 1.36%/year), and the expected growth in demand (all commodities, all uses, 1.1% annual growth), which incorporates the expected shift in developing countries to more meat-based diets.

3. Estimates of agricultural yields are moderate but consistent with historical trends (1.1% per year). In other words, the FAO does not meet 2050 demand (which includes significant improvements in per capita food consumption) by assuming unrealistic productivity improvements.
4. The estimate does not meet 2050 food demand by assuming an implausible conversion of land to agricultural uses, a problem in some biophysical models. (The FAO assumes 70 million hectares are converted by 2050, a 9% increase.)
5. The FAO validates its projections against data for more recent years and against the FAO-OECD ten-year projections to 2020 (OECD-FAO 2011).

Thus, the latest FAO estimates present substantial reassurance that with the right policies (investment, agricultural research, etc) global agriculture is capable of meeting projected demand (food and non-food uses) in 2050. What, then, are the caveats? The business-as-usual assumptions inherent in this approach leave two major issues poorly addressed.

1. Biofuels expansion – The FAO model is concerned primarily with food supply and demand, though the researchers estimate total agricultural supply and demand for all uses (food, feed, industrial non-food, seed - including an allowance for waste). As such, biofuels scenarios do not get the attention they deserve. To arrive at their 60% estimate, the FAO assumes biofuel expansion to meet existing mandates through 2020, then no further expansion beyond that. This is both unrealistic and, from the perspective of policy-makers, unhelpful. Current estimates project first generation biofuel demand in 2030 to be double the FAO's assumed levels (IEA 2012). Policy-makers would be best served by analysis showing the impact of different biofuels policies and scenarios.
2. Climate change – The authors acknowledge, with due apologies, that they were not able to incorporate into their modeling the impacts of climate change on agricultural production. Given that even with perfect mitigation today we would expect to see measurable climate change by 2050, the FAO projections are in need of significant adjustment. As the authors acknowledge, "In principle, a scenario that assumes no climate change has no place in the array of scenarios to be examined." (p. 93)

Obviously, these are not trivial shortcomings. Both suggest that the FAO projections err on the side of overestimating food availability, as both trends suggest negative impacts at a global level.

These issues, and a range of others, were addressed at a 2009 expert meeting convened by the FAO to assess the implications of the food price crisis for our ability to meet future food needs. The meeting brought together researchers from key institutions relying on a wide range of models. The resulting papers were later published as a book, *Looking Ahead in World Food and Agriculture: Perspectives to 2050* (Conforti 2011). The volume includes some valuable updates on the 2009 papers and added material and analysis, including a comparison of the main models and an assessment of their differences and relative strengths and limitations. As such, it represents one of the more comprehensive efforts to gather and assess the results from a range of researchers and models.

It is beyond the scope of this paper to summarize the rich results from this collective work. Here the goal is to broadly characterize the important modeling contributions, note some of their most important results, and identify some of their strengths and limitations in relation to the broader goals of projecting future agricultural production and consumption and identifying the key trends that are susceptible to policy influence.

Alexandratos (2011) provides an excellent comparison of the main modeling efforts contained in the FAO volume. They include:

- FAO's partial equilibrium model of supply and demand, as outlined above. This also includes important FAO modeling on land, water and other resource constraints (similar to that in Alexandratos and Bruinsma 2012), based on the FAO's and IIASA's GAEZ assessment on the availability of land of varying suitabilities for crop production.
- World Bank projections, using its GTAP-based ENVISAGE general equilibrium model to examine the implications of economic growth scenarios, agricultural productivity growth, poverty, and the potential impacts of climate change and energy markets on those results.
- A more pessimistic assessment of some of these same economic issues, particularly as they relate to poverty.
- IFPRI's detailed modeling of climate change impacts on agriculture using its partial equilibrium IMPACT model.
- Work by the International Institute for Applied Systems Analysis (IIASA), using its general equilibrium model, to carry out detailed modeling of both climate and biofuels scenarios.

Alexandratos provides a useful guide to the differences in these models and the reasons for their differing results in terms of projections to 2050 as far as such reasons could be identified from the contents of the papers and communications with selected authors. Concerning price projections of the baseline scenarios, he finds some agreement among the models in their projections of supply and demand and world prices. (In most economic models, price is the key measure, as it is where the models resolve imbalances between supply and demand.) Interestingly, these show greater price moderation than most current characterizations of ongoing high food prices. These models generally show prices lower than the "post-surge" prices of recent years, generally in line with "pre-surge" price levels through 2030, then rising by 2050 to about 30% above pre-surge prices. Those are still well below current post-surge price levels.

Modeling results to 2050 are, of course, sensitive to economic growth assumptions, with faster economic growth increasing demand at a faster rate. The World Bank modeling tends to be optimistic in this area, assuming an average growth rate of

1.6% for high-income countries and 5.2% for developing countries (van der Mensbrugghe, Osorio-Rodarte et al. 2011, p. 206). The model is also more optimistic about agricultural productivity growth, assuming 2.1% growth in total factor productivity, assumed to come as a result of technological innovation. Neither takes account in any detailed way the resource constraints on growth and productivity, though the World Bank modelers adjust their overall agricultural productivity growth rate to 2030 downward from 2.1%/year to 1.76%/year to account for climate change.

Hillebrand (2011) offers a more sober assessment, producing a "market first" high-growth scenario, similar to the World Bank assumptions, and a low-growth scenario that assumes that developing countries grow at the rates comparable to the pace of the previous 25 years. This "trend growth" scenario for developing countries produces sobering results, as the slowest growing regions continue to grow slowly (see Table 1 below, from p. 183). His metric is poverty, and he estimates that with trend growth extreme poverty worldwide would be 20% instead of the 2.6% assumed in the "market first" scenario. The same scenarios also highlight just how different regional performance can be. Under the "trend growth" scenario, Sub-Saharan Africa would have 53% of its people in extreme poverty – a higher percentage than in 2005 – instead of 12% under the more optimistic scenario; 78% would fall below the $2.50/day poverty line.

Table 1. High and low growth scenarios (from Hillebrand 2011, p. 183)

Table 4.10
Poverty in the slow-growth regions: comparison of scenarios

	2005		2050 market first scenario		2050 trend growth scenario	
	USD 1.25/ day	USD 2.50/ day	USD 1.25/ day	USD 2.50/ day	USD 1.25/ day	USD 2.50/ day
	(millions of people below the poverty threshold)					
Latin America	46.1	122	7.8	21.1	56.9	147
Near East and North Africa	11	86.7	0.7	2.5	9.4	48.1
Sub-Saharan Africa	391	614	205	533	930	1 364
World	1 377	3 085	245	710	1 120	1 948
	(% of population)					
Latin America	8.4	22.1	1.0	2.7	7.4	19.2
Near East and North Africa	3.6	28.4	0.1	0.6	1.7	8.9
Sub-Saharan Africa	51.2	80.5	11.7	30.5	53.1	77.9
World	21.3	47.7	2.6	7.6	12.0	20.9

Sources: 2005 figures from Chen and Ravallion, 2008; 2050 figures from author's calculations.

Hillebrand usefully warns of modeling assumptions that solve all resource constraints through technical change. As the FAO's Conforti notes in his introduction to the collection of studies, "catching up is not a necessary outcome, especially if institutions and investment are not adequate" (Conforti 2011, p. 5).

Indeed, Fischer, Byerlee et al (2012a) warn that there is little evidence that genetic engineering will significantly improve yields in the next thirty years, so closing yield gaps using existing technologies becomes a high priority. They estimate that we need annual average yield growth of 1.25% to meet global food needs in 2050. (Note, however, that the latest FAO projections to 2050 estimate that the world average cereals yield would need to grow only at 0.7% per year to meet 2050 demand (Alexandratos and Bruinsma, 2012, Table 4.13).

Alexandratos notes wide variations in assumptions about consumption levels too. Some of this results from reliance on older or unrealistic historical data used in the models' base years and some from varying assumptions about economic growth, to which all economic models are particularly sensitive. He considers IFPRI's consumption projections too low for those reasons, while he finds IIASA's too high due to a high initial baseline estimate. He recommends the FAO's estimates as more realistic, since they rely on more up-to-date historical data and they have been validated against more recent consumption figures and against OECD/FAO projections through 2020.

The other variable that has great influence on modeling outcomes is population growth. The greater the population, the greater the demand for agricultural products. FAO uses a 2050 estimate of 9.15 billion people, which is based on the middle path among three United Nations population scenarios, from the 2008 UN population revision. The researchers recognize, though, that uncertainty persists and different trends would change the projections significantly. Interestingly, Alexandratos notes that among the models the FAO includes in its volume there is wide variation in population assumptions and these underlie some of the differences in results. For example, one scenario assumes climate change associated with GHG originating from a scenario (the IPCC SRES A2 scenario) which has a 2050 population of 11.3 billion. He finds different population assumptions (implicit or explicit) even within the same model, and he recommends greater attention to clear and consistent use of population assumptions.

Tomlinson (2011) offers a useful critique of what she calls the "new productivism" driven by economic models that raise alarms about looming shortfalls in global production, echoing a Soil Association (2011) critique of the earlier 70%-100% figures widely cited. As she points out, "increasing production on such a scale was never intended as a normative goal of policy and, secondly, to do so would exacerbate many of the existing problems with the current global food system" (p. 1). She warns of prior ideological commitments to a particular framing of the food security issue, which defines food security as an issue of production rather than access and utilization. She also notes:

- Most such estimates overstate future food needs because they derive volume needs from value calculations. As higher value foods such as meats grow in the share of global diets, this can overstate the needed volume increases. It has been estimated, for example, that if weight were used instead of value, estimated needs would be reduced by 6% (DEFRA 2010). (The latest FAO projections address this issue – Alexandratos and Bruinsma, 2012, Boxes 1.1 and 3.1.)

- Fruits and vegetables are generally excluded from these projections, mainly because they are not treated as commodity crops (Wright 2010). (The latest FAO projections do cover fruit and vegetables as separate products.)
- The measure used in many studies is based on per capita food consumption in calories, derived from estimates of availability. Such food availability projections allow for broad trend estimates but they neglect demand-side issues such as food waste, not to mention unequal access and distribution (Barrett 2010).

Tomlinson recommends looking beyond such economic models to efforts that take into account concerns for health, equity, and the environment and that model alternatives to what she refers to as "productivism."

The challenge of long-term economic modeling

The studies and analysis in the FAO's collection are a good representation of the economic modeling that has generated some of the most widely cited estimates of food needs in 2050. Alexandratos's observations highlight the challenges inherent in such long-term modeling and the sensitivity of the results to modeling assumptions about variables of great uncertainty – economic, environmental, and those related to policy. Indeed, often such assumptions are made explicit only in technical annexes to the studies, and sometimes not at all. The results, however, are generally presented with a high degree of certainty. They are often then repeated as definitive by policy-makers and the media in their efforts to simplify complex topics. Such is the case with the studies estimating agricultural production and demand to 2050.

Indeed, Reilly and Willenbockel (2010), in an excellent overview of food system modeling, warn of this precise problem. "Model outputs should not be misinterpreted as forecasts with well-defined confidence intervals. Rather they are meant to provide quantified insights about the complex interactions in a highly interdependent system and the potential general size order of effects, which cannot be obtained by qualitative and theoretical reasoning alone." (p 2053)

They point out that such modeling requires the mapping of one uncertain system – agricultural production and consumption – with another – ecosystems. Both are characterized by gaps in data and knowledge, limited confidence in predicting the future from the trends of the past, and instability regarding future systems behavior. One set of uncertainties compounds the other, leaving, logically, a virtually unlimited range of possible outcomes. This is true just considering the "known unknowns," such as the extent to which rising CO2 levels have some positive effects on agricultural production (CO2 fertilization) or whether agricultural productivity growth will be high or low by historical standards. Add in the "unknown unknowns," such as extreme but low-probability climate events, and the forecasting potential for long-range modeling is necessarily limited.

A final cautionary warning is echoed by most researchers involved in such modeling. Global estimates of our ability to "feed the world" rely mostly on global estimates of supply and demand, yet ecosystems and agricultural production occur at local and regional scales. So too does hunger. Thus, global estimates of "our" ability to feed "the world" immediately break down[4], begging the more important questions of how these systems develop across widely differing landscapes, societies, and levels of economic development, and how equitably the food is then distributed. In the end, "the world" is not fed, in aggregate, and there is no collective "we" doing the feeding.

Still, even if the prevalent misinterpretations of modeling results should be discounted, such efforts still have a great deal to offer to those struggling to identify the paths forward. At best, they can challenge the "mental maps" of policy-makers by drawing out plausible real-world implications of business-as-usual policies or alternative approaches. They can also assess the relative importance of different drivers of change.

From the economic modeling world, Thomas Hertel presented a refreshing set of observations on the state of current agricultural modeling as part of his presidential address to the Agricultural and Applied Economics Association in 2011 (Hertel 2011). In a number of ways, his observations echo those of the FAO study cited earlier:

- Income growth is a key variable and it has proven quite stable over time, though we now see faster income growth in (some) developing countries than in wealthy countries. That has implications for changing diets and increasing demand, but these relationships are relatively well understood and, while subject to change, are less difficult to model.
- Yield growth has slowed, as many have noted, but he sees no cause for alarm. He cites cautionary studies, e.g. Fischer, Byerlee,and Edmeades (see updated version in Fischer, Byerlee et al. 2012b) who note that the growth of yield potential in two dozen "breadbasket" regions of the world has slowed to less than 0.5% annually. But he agrees with the FAO that yield growth is basically keeping up with slowing long-term growth in demand.
- Yield potential varies considerably by crop and region, but in general yield gaps are low on current irrigated land, which generally operates at 80% of yield potential and accounts for 40% of global crop production. There is much greater potential for gains on rain-fed land, where yields are often below 50% of potential (Lobell, Cassman et al. 2009). He cites studies showing that bringing such lands up to their potential, on current cultivated land and using existing technology, would generate production increases in 2050 of 60% for wheat, 50% for maize, 40% for rice, and 20% for soybeans (Monfreda, Ramankutty et al. 2008; Licker, Johnston et al. 2010). Most such lands are in less developed regions of developing countries, representing both an obstacle (resources) and an opportunity (reducing hunger and poverty).

[4] The FAO study assigns particular importance to this point: "... examining the issue of food insecurity by means of global variables (e.g. can the world produce all the food needed for everyone to be well-fed?) is largely devoid of meaning" and "In conclusion, the issue whether food insecurity will be eliminated by the end of the century is clouded in uncertainty, no matter that from the standpoint of global production potential there should be no insurmountable constraints" (Alexandratos and Bruinsma, 2012, p. 20-21)

- Urbanization will have a significant impact on the available supply of land in key developing countries such as India and China, but globally it may not present as large an impact on available land as some suggest (p. 267).

Hertel provides some useful critiques and suggestions for future modeling. He highlights the importance of long-term elasticities of food demand for agricultural land use, that is, how rising demand can be expected to translate into land conversion. He cautions that many economic models may be overstating the land use implications of rising agricultural demand by using elasticities that are too high. Hertel also echoes the oft-repeated cautions about modeling the uncertainties associated with bioenergy production and climate change. He points out that Searchinger (Searchinger, F. Dong et al. 2008) overstated indirect land use change because he failed to fully account for yield intensification as demand rises. But he notes that in the long run global oil prices will be the main determinant of demand for biofuels. With estimates to 2030 ranging (at his writing) between $50 and $200/barrel, the uncertainties are extreme. All the more so with climate uncertainties, and he cites studies that show a wide range of estimates (see, for example, Hertel, Burke et al. 2010).

A forthcoming special issue of *Agricultural Economics* makes an important contribution to this effort. The issue brings together analysis from the Agriculture Modeling Improvement Project (AgMIP), a collaborative effort to improve global agricultural modeling particularly as it relates to key uncertainties such as climate change and bioenergy production. The issue compares results from ten different models by harmonizing some of the key assumptions in the models - population growth, GDP growth, agricultural productivity growth, energy prices, base years - then introducing alternative socio-economic, climate change, and bioenergy scenarios.[5] While the goal is to thereby improve modeling by identifying the important differences in the modeling assumptions (controlling for those variables), the comparison offers a rich set of results across a range of economic models. The authors are clear that the simulations are not necessarily grounded in the most realistic scenarios. Still, they permit a number of important conclusions, which are summarized in the overview chapter generously made available to us for this review (von Lampe, Willenbockel et al. 2013).

Their conclusions and findings include:

1. The underlying assumptions, which the AgMIP comparison controlled for, account for significant differences in modeling results. Controlling for them narrowed the range considerably. The baseline scenario, which did not include climate change impacts, echoed the FAO's estimates that while agricultural

[5] Models participating in this comparison include: Asia-Pacific Integrated Model (AIM) from the Japanese National Institute for Environmental Studies; ENVISAGE, based on the World Bank's LINKAGE model, now housed at the FAO; Emissions Prediction and Policy Analysis (EPPA) from MIT; Global Trade and Environment Model (GTEM) from the Australian institute ABARES; Future Agricultural Resources Model (FARM) from the USDA; Modular Applied GeNeral Equilibrium Tool (MAGNET) from Wageningen University; Global Change Assessment Model (GCAM) from the Pacific Northwest National Laboratory; Global Biosphere Optimization Model (GLOBIOM) from IIASA; IFPRI's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT); Model for Agricultural Production and its Impact on the Environment (MAgPIE) from the Potsdam Institute for Climate Impact Research.

commodity prices would not likely resume their decline from the 1960s-2005 (reported as -4%/year in real terms), there was general agreement among the models that price increases would be quite limited (estimates ranged from -0.4%/year to +0.7%/year). This reflects a range of 60%-111% estimates for increases in world agricultural production from 2005-2050.

2. All of the controlled variables have great impact on results well out in the future, such as in 2050 scenarios. While we know a great deal about them, and the historical data is relatively good in most cases, all present important uncertainties that cannot be resolved conclusively. A scenario changing the assumptions from "middle of the road" to a higher population, lower GDP growth scenario showed just how much worse the outcomes could be for production, consumption, and prices. If population in developing countries grows 11% more by 2050 and GDP growth is more than 30% lower due to slowed annual growth rates over time, per capita calorie consumption will be significantly lower - 6-10% globally, and much lower than that in poorer regions.

3. In contrast to many earlier estimates, climate change scenarios showed clear negative impacts on yields at the global level. The scenarios modeled were acknowledged to be "worst case", with high temperature change and no CO2 fertilization. But models generally showed negative impacts on yield and production, with resulting higher prices. Price estimates ranged among the models from +2% to +79%. Per capita calorie availability declines across the globe, and some of the more extreme estimates suggest they could be as much as 11% lower for India compared to the "no climate change" baseline.[6] (As some have pointed out, this latter finding may not be credible, which underscores the importance of the AgMIP modeling improvement effort.).

4. Demands from second generation bioenergy production are projected to have relatively modest impacts on food production, consumption, and prices, far lower than the impacts of climate change. Agricultural commodity prices are estimated to be less than 9% higher with significant second-generation bioenergy development. Unfortunately, the scenarios modeled here compared only post-2030 scenarios on second-generation bioenergy development, leaving an assumed and unexplored growth in first generation biofuels through 2030, and then continuing at that level to 2050. Thus, the implications of first generation expansion go largely unaddressed, though it is worth noting that this baseline scenario posits higher biofuel demand than most of the other models that report results to 2050. (We return to that when we examine modeling on bioenergy production.)

[6] The authors note that the crop models assumed the absence of any fertilization effects of higher atmospheric contents of CO2, meaning that the results are based on a "worst-case" pathway from the range of possible climate change developments.

The authors conclude with the important recommendation that scenario modeling is critical for policy and investment decisions, so "it will be necessary to bring decision-makers and modeling groups closer to improve exchange and dialogue between them."

The broader world of modeling

Reilly and Willenbockel (2010) provide a useful typology of such modeling and a detailed analysis of what it offers.[7] They distinguish between projections, exploratory scenarios, and normative scenarios. Projections include efforts like the FAO's and most of the other studies reviewed thus far. They include baseline modeling, such as the FAO's, as well as what the authors refer to as "what if" scenario modeling in which one or two factors are altered to assess the importance of that factor, e.g. the kind of climate and biofuels scenarios explored by Fischer.

Exploratory scenarios involve the introduction of a more complex and related set of changes. Examples include the incorporation of "external" inputs, such as in Parry, Rosenzweig, et al.'s (2004) modeling of IPCC climate scenarios. These also include what the authors call "strategic" scenarios, as in the Millennium Ecosystem Assessment modeling (Carpenter, Pingali et al. 2005). As the evocative scenario names suggest – Global Orchestration, TechnoGarden, Order from Strength, Adapting Mosaic – these attempt to model the implications of varying paths for global society.

Normative scenarios take this approach further by starting with the desired paths then modeling the implications of each of them for key parameters, from water and land use to climate mitigation and food production. The authors distinguish two types of normative scenarios. "Preserving" scenarios model efforts to achieve outcomes while preserving the essential features of the current system, such as de Fraiture, Wichelns, et al.'s (2007) scenario of optimal investment in water resources. "Transformative" modeling is similar to the "strategic exploratory" scenarios mentioned above but the researchers define a desired future and model what it would take to get there. One of the more comprehensive such efforts is the Agrimonde project, which defined a sustainable and equitable food system for 2050 and modeled what it would take to achieve those goals (Paillard, Dorin et al. 2011; Paillard, Treyer et al. 2011).

Each of these approaches offers valuable insights. The normative modeling may be the most provocative because it tends to highlight how far our present path is from what is optimal if we want to achieve a particular goal. Similarly, "strategic" modeling charts distinct paths, futures, and implications, offering sometimes stark contrasts in outcomes from different societal trajectories.

This is invaluable as societies confront complex challenges, such as the carrying capacity of the planet. In both cases, however, the complexity of the changes being modeled makes it difficult to determine from the results the outcome of any one discreet

[7] The authors review a range of global scenario studies including the FAO long-run projections, CAWMA, Agrimonde, a study by Parry that uses IPCC socio-economic scenarios, and the Millennium Ecosystem Assessment (MA) scenarios.

factor, and policy-makers are – for better or for worse – generally trying to address factors in isolation. For example, it is impossible to infer from the Agrimonde modeling what the optimal biofuels policy (or even goal) should be to achieve a sustainable and equitable food system, because the model includes changes to so many other factors. In fact, Reilly and Willenbockel cite a small body of literature on the impacts on decision-making of such modeling, which suggests very limited policy change (see p. 3060).

Reilly and Willenbockel note other relevant typologies, such as Cumming's (2005) for integrated environmental assessments. These include: "Market forces" – defined by economic growth being of paramount importance; "Reformed market" – with greater government regulation to address externalities; "higher fences" – with rising protectionism; "values change" – broad progress toward equity and sustainability; "multipolar world" – characterized by a rise in regionalism. They cite the predominance of "market forces"-type assumptions in economic models, which may limit the value of such research for policy-making. Van Vuuren comes to similar conclusions, synthesizing a set of archetypal scenarios that share common features, and often results (van Vuuren, Riahi et al. 2012). Thompson and Scoones' (2009) offer a more detailed critique of the direction of social science research on food systems. These authors call for more multi-disciplinary approaches that look beyond economic growth and focus on sustainability and participatory research.

Van Dijk (2012) provides a valuable assessment of food systems modeling with a focus on food security outcomes. He concurs that climate change and biofuels are poorly incorporated into long-term assessments. And he points out that most modeling focuses on the production side with inadequate attention to consumption. "These indicators only partially cover the dimensions of food security and predominantly focus on food availability and accessibility, while utilisation is hardly addressed (apart from the very basic indicator of child malnutrition) and stability is completely omitted." (p. 20) He refers to promising new efforts (Food Secure Project) to incorporate detailed household survey data on consumption into such analyses.

Modeling that begins with a more narrowly defined question, and therefore a narrower range of parameter changes, can be more useful to policy-makers (e.g., optimal investment in water resources). For policy-making, it may well be that "what if" scenario modeling is the most useful. If the baseline established by the model is transparent and realistic and considers the uncertainties inherent in such long-range efforts, the introduction of a limited set of plausible policy or parameter changes can identify a range of possible impacts. These, in turn, can inform policy-makers as they consider discreet alternatives. We return to this below when we explore the policy-relevant modeling related to feeding the world in 2050.

Scenario modeling of key drivers of change

If one goal of scenario modeling is to inform policy-makers about the consequences of their policy decisions, the question of feeding the world in 2050 raises several key policy questions. All of the variables that drive 2050 modeling results have policy implications, but some are more directly subject to policy changes. As we have seen, the level of GDP growth has a significant impact on the 2050 outcomes, yet the policy levers to achieve faster or slower growth are multiple and complex. Similarly, population growth drives 2050 projections, and while we know that many factors – economic development, women's education and empowerment, etc. – lower birth rates, these strategies and their paths are relatively well-researched.

Here we focus on the 2050 modeling to assess the extent to which other policy-related drivers have been well-modeled to allow policy-makers to better assess their decisions. In particular, we examine scenario modeling on:

- **Agricultural productivity growth**, which is closely related to investments in research and development, extension, irrigation, and other areas germane to public policy;
- **Biofuels expansion**, which is a key variable, both in terms of the extent of first generation biofuel production and in terms of the transition to more sustainable second generation technologies.
- **Climate change**, which presents modelers with a daunting range of uncertainties in projecting agricultural production to 2050 and beyond.

Agricultural productivity

As we have seen, modeling of agricultural production to 2050 is extremely sensitive to assumptions about agricultural productivity growth. Over a 40-year time horizon (2010-2050) each 0.1% change in the assumed rate produces a 4% change in total output. If uncertainty were assumed to be within a range of plus-or-minus 0.25%, the resulting production levels come with a range of plus-or-minus 11%. Higher assumptions (e.g., van der Mensbrugghe, Osorio-Rodarte et al. 2011) therefore assume a great deal more available food in 2050. More pessimistic assumptions (e.g., Hillebrand 2011) can generate panic about food availability into the future. Many uncertainties plague attempts to estimate agricultural productivity growth: climate change, levels of agricultural investment, effectiveness of agricultural investment, etc. Still, historical trends offer some reliable baselines for assessing future growth, and public policies can increase growth.

Most scenario modeling on agricultural productivity creates simulations to illustrate the importance of agricultural productivity growth without basing those scenarios on documented impacts of public policies (or other changes). These are instructive because they highlight the importance of, for example, investment in agriculture. But their results are less relevant to assessing policy impacts, nor do they offer reliable forecasts of alternative paths.

Willenbockel (2011), for example, develops an interesting baseline scenario to 2030, then imposes a scenario in which productivity growth is 50% higher for all crops in all regions. Not surprisingly, projected price increases moderate significantly with such a jump in agricultural productivity. This supports the argument for greater investment in agriculture, even though the assumption of 50% higher productivity growth is not based on a careful assessment of either the impacts of agricultural investment on productivity nor the regional and crop variations in responses to such investment. Still, such a "what if" scenario is useful in calling attention to the importance of the issue.

World Bank modelers did similar "what if" simulations off their baseline scenario, which began with the optimistic assumption of global annual agricultural productivity growth of 2.1% (van der Mensbrugghe, Osorio-Rodarte et al. 2011). Their model produced the outcome of broad supply and demand balance with slight declines in prices as the indicator. In one scenario, they cut agricultural productivity in the developing world by half, with the result that global agricultural prices would rise 16% by 2030. They then ran a scenario in which global productivity is cut by half, and the result was a 35% price increase to 2030, not surprising since a one percentage point drop in productivity over forty years cuts global production by 34%. (Interestingly, this latter scenario, with global productivity growth of 1.05%, is more in line with the baseline assumptions in many of the other models.) Again, this type of modeling highlights the importance of agricultural productivity to meeting global food needs, even if it does not necessarily base those scenarios on specific policy actions or external modeled trajectories for agricultural productivity.

IFPRI used its IMPACT model to simulate various scenarios, including one of higher agricultural productivity growth resulting from a range of investments (Nelson, Rosegrant et al. 2010). Higher productivity (global averages were not clearly specified) reduced projected 2050 price increases for the three main grains from a range of 54%-101% to 20%-60%. As the authors point out, this would have significant impacts on child malnourishment, one of their key metrics. So too would increases in productivity growth for key staple crops of maize, wheat, and cassava, and increases in irrigation efficiency, all of which were separately modeled. A more recent IFPRI scenario assumed productivity increases that would reverse expected price increases, yielding an estimated 8% reduction in the number of malnourished children in 2050 compared to the business-as-usual scenario, and a 24% reduction in the population at risk of hunger (Rosegrant, Tokgoz et al. 2013, p. 95).[8] Again, these are useful less as forecasts than to highlight the potential impacts of agricultural investments.

The multiagency IAASTD project did only limited modeling for its comprehensive report calling for a dramatic shift to more sustainable practices (IAASTD 2009). But researchers used the IMPACT model to gauge low and high agricultural investment pathways to 2050. Their reference case productivity assumption of 1.02%/year resulted in crop price increases 22%-42% for the three main staple grains. The low investment scenario, with annual productivity growth cut to 0.41%, left astronomical supply shortages, with projected price increases of 303%-1,292%. The high productivity scenario, with 1.63% annual productivity growth, projected significant crop surpluses, with modeling projections of price decreases from 48%-73%. These unrealistic high and low price projections serve less as forecasts and more as demonstrations of the importance of agricultural productivity, and the necessary agricultural investment IAASTD was advocating.

[8] The same study modeled scenarios of higher energy prices and lower meat demand.

Later we review some modeling on climate change, which is relevant to this discussion since one of the primary uncertainties is the climate impact on yields.

Biofuels expansion

It is somewhat surprising that there has not been more careful modeling of the impacts of biofuels expansion on 2050 food production. There is widespread agreement that it is an important variable. Unlike the case of climate change, the uncertainties in modeling biofuel demands on agricultural resources are relatively well known. They relate less to uncertainties about biophysical inputs or responses to changing conditions. The impacts in the case of first generation biofuels are direct, in terms of crop diversion and land use. Policies such as consumption mandates are clear and in place. And the trajectory, at least over the period of those mandates (10-12 years), is well specified. Variables include: changes to those policies, energy prices, and the timing, scale, and impact of the emergence of second generation biofuels.

One reason many of the 2050 models take inadequate account of biofuel expansion is the difficulty of incorporating such a recent phenomenon into scenario modeling that necessarily relies on somewhat dated base years. Many 2050 models have a base year of 2000, years before the biofuel boom. Even the relatively updated models, with 2005 base years, do not capture much of the recent surge in biofuel production. To the extent such models fail to account for biofuel expansion in their scenario exercises, their results will be of limited use. In any case, their results will be driven to a significant extent by the assumptions they make about biofuel expansion. For example, the FAO in its 2012 update incorporated more up-to-date estimates, but they assume the expansion to 2019, based on OECD/FAO projections, then no further expansion to 2050. They acknowledge that this likely underestimates biofuel demand, which they correctly note will be driven significantly by oil prices.

The detailed effort by Fischer (2011) presents an example of the kind of "what if" scenario modeling that policy-makers need to evaluate key issues such as biofuel expansion, though it is now quite out of date. Using a modeling framework based on the FAO/IIASA Agro-Ecological Zone (AEZ) model and the IIASA World Food System model, Fischer models a series of biofuels expansion scenarios in addition to several climate change scenarios. The results may appear dated, relying on base year data from 2000 and incorporating additional data only up to 2008, but the results are indicative of the consequences of policy and pathway choices. Here we summarize the key scenarios and results.

Table 2. Modeling Biofuel Scenarios

Modeling Biofuel Scenarios

Scenario Name	Description	Change in 2050 Price Index (%)	Added People at Risk of Hunger in 2030	Land Use Change 2050(%)[2]
FAO-REF-01	Freezes expansion at 2008 levels[1]			
WEO-V1	IEA 2008 projections; 2nd generation from 2015	7	21 million	21
WEO-V2	WEO-V1, no 2nd gen. until 2030: all demand to 2030 from 1st gen.	11	42 million	29
TAR-V1	WEO-V1, but mandates fulfilled by 2020: doubles demand for 1st gen.	20	136 million	48
TAR-V3	TAR-V1, but quick 2nd gen: 33% global demand in 2020, 50% in 2030	9	74 million	29
SNS-V1	Scenarios based on share 1st gen. in transport fuels 2020, 2030, 2050: Low - 2%, 2.5% and 3%	4	-	-
SNS-V2	Medium: 4%, 5%, and 6%.	13	-	-
SNS-V3	High: 6%, 7.5%, and 9%	23	-	-
SNS-V4	Very high: 8%, 10%, and 12%	35	-	-

[1]Ref scenario: Price Index (1990 = 100): 115; Risk of hunger: 458 million; Cultivated land: 1.7 billion ha
[2]Relative to reference scenario of no agricultural crops used for biofuel production
Source: Fischer (2011)

The results are instructive (see Table 2). To tell the story in a narrative form, compared to the very conservative and outdated baseline, the WEO-V1 scenario, which uses 2008 International Energy Agency projections for demand, shows that even moderate additional biofuel demand over 2008 levels raises prices 7%, increases those at risk of hunger by 21 million people, and requires a 21% increase in cultivated land, even with early and gradual deployment of second generation biofuels. If advanced biofuels are not available until 2030 (WEO-V2), prices increase 11%, hunger risks rise to 42 million, and there is a 29% increase in cultivated land. In other words, delays in the deployment of advanced biofuels have serious implications.

TAR-V1 uses more realistic estimates of demand, based on known mandates and targets. This raises projected biofuel demand by 100%, with dramatic results – 20% price increase, 136 million at risk of hunger, 48% increase in cultivated land. Only the rapid deployment of advanced biofuels (TAR-V3) mitigates these impacts, with only 9% price impacts, 74 million more people at risk of hunger, and still a 29% increase in cultivated land.

The four sensitivity analyses (SNS V1-V4) show the increasing impact on agricultural prices of different expansion scenarios for first generation biofuels, from 4% in the low case to 35% in the high case. Note that based on current estimates, the medium scenario (SNS-V2) may well be the closest to our current path.

This modeling is not perfect, of course. The base year is outdated, so it makes sense to use the results to gauge the price impacts of the different scenarios in relation to one another, not so much in relation to the base year. In addition, Alexandratos (2011) points out that the model overestimates consumption levels overall, which raises demand in relation to supply. And he suggests that land is modeled inadequately, with additional demand translating too readily into additional cultivated land and with little accounting for the land needs of second generation biofuels. He also suggests that the model does not adequately account for supply responses by farmers to higher agricultural prices, nor the impact of oil prices on biofuel demand. Notably, only rain-fed land is included in this modeling run.

Still, it is easy to see why this sort of "what if" scenario modeling can offer policy-makers a relatively clear picture of the consequences of their policies. If we want to feed the world affordably by 2050 we need to speed up the development and deployment of advanced biofuels and/or slow demand for first generation biofuels by reducing mandates. Otherwise we are putting undue pressure on poor consumers (via price hikes) and on the environment (via land and other resource demands).

Again, it is surprising that more up-to-date modeling has not been carried out on an issue as important as biofuels. The table below shows just how outdated most modeling assumptions are in comparison to the World Energy Outlook's 2012 projections for first generation biofuels use. The FAO uses FAO-OECD projections to 2020, which are consistent with WEO estimates, but then holds them constant through 2050. This leaves the 2030 assumption at less than half of projected use. The IMPACT model reviewed earlier uses old base year assumptions and minimal growth. The World Bank projections do not explicitly account for growing biofuel use. The more current AgMIP project assumes trend growth through 2030, which results in estimates comparable to WEO's.

Table 3. Wide variation in estimates of biofuels expansion

Projected Cereal Use for 1st Generation Biofuels

(millions tons)

Model	**Scenario**	**2010**	**2020**	**2035**	**2050**
WEO 2012[1]	Current Projections	148	239	421	na
Reviewed Models		**2008**	**2020**	**2030**	**2050**
FAO	Alexandratos (2012)	65 (2005)	182	182	182
IMPACT[2]	Msangi (2011) Baseline	20	75	110	110
World Bank[3]	van der Mensbrugghe (2011)	n/a	n/a	n/a	n/a
AgMIP[4]	baseline, 1st generation	148	273	397	397
IIASA	FAO-REF-01 (2008 levels)	83	83	83	83
	WEO-V1	83	181	206	246
	WEO-V2	83	192	258	376
	TAR-V1	83	327	437	446
	TAR-V3	83	238	272	262

1 2010 actuals from FAO-OECD (2012); WEO 2012 projected growth rate to 2020, 2035

2 Drawn from Alexandratos (2011), pg. 48

3 Numbers not currently available; Author assumes fulfillment of mandates as of 2009

4 2010 actuals from FAO-OECD (2012); AgMIP growth rate for other years (Lotze-Campen 2013)

As Table 3 shows, of the IIASA scenarios modeled by Fischer, his worst-case scenario (TAR-V1) seems the closest to business-as-usual projections, at least for 2030. That model assumes the fulfillment of mandates and the slow deployment of advanced biofuels. But that modeling needs to be improved to be useful. Updating Fischer's base year and modeling parameters, addressing the shortcomings noted by Alexandratos, and shifting scenarios somewhat to reflect current policy considerations would yield a useful set of results to allow policy-makers to better manage biofuel expansion so that it does not impede our ability to feed the world in the future.

As part of the AgMIP project mentioned earlier, Lotze-Campen, von Lampe et al. (2013) carried out a comparison of five models in which basic parameters are controlled, first generation biofuels are assumed to expand at their current rate through 2030 then hold constant, but two scenarios are modeled, one with low second generation deployment after 2030 and one with high deployment. The authors estimate modest price impacts (9%) of advanced biofuels on agricultural prices suggesting that the additional pressure on prices from advanced biofuels will be significant but lower than for first generation biofuels. If advanced biofuels replace first generation biofuels (not assumed in this modeling), the impacts on prices and resource use would be much lower.

Climate Change

Climate change is one of the most difficult variables to model. The difficulties stem from the layered uncertainties associated with climate change and its impacts on agriculture. First, there is uncertainty about the extent and timing of climate change likely to result from current levels of emissions. Second, projections to 2050 and beyond must account for uncertainties related to the extent and pace of mitigation going forward, including whether global policy changes will reduce emissions and future impacts. Third, the impact of such temperature changes on the earth's ecosystems is only imperfectly understood. Fourth, there is great uncertainty about the impacts of such changes on agricultural production. Fifth, it is difficult to predict with any certainty what adaptation measures will be taken and how effective they will be. Finally, impacts are expected to be worse over time, making the 2050 time horizon too short to adequately gauge climate risks.

Wright (2010) provides an extensive review of the literature on climate mitigation and the potential impacts on our ability to feed the world in 2050. She finds few studies that address the intersection of these two questions, but a good deal on each individually. Here we simply highlight some of the scenario modeling that illustrates the state of the art while also demonstrating the profound difficulties of dealing with so many uncertainties.

As with scenario modeling for other key variables, some research is intended less to forecast possible outcomes than to demonstrate the importance of the issue through quantitative methods. Willenbockel (2011) relies on an impressive range of external estimates of the productivity impacts of climate change to 2030, by region and crop (see p. 26 for estimates and sources). The assumptions are pessimistic, based on relatively high temperature changes and sensitivity of crops to warming, and relatively low CO2 fertilization effects. Compared to his reference scenario, price increases are significantly higher in 2030 for the main grains (about 140% compared to about 90%), highest for maize. And the impacts are especially severe in Sub-Saharan Africa.

Interestingly, Willenbockel adds a scenario of successful climate change adaptation in Sub-Saharan Africa. He assumes that adaptation measures restore agricultural productivity levels in this region to those in his non-climate-change reference scenario. Price increases are significantly moderated, even with the assumed failure of mitigation or adaptation efforts in other parts of the world. He concludes from this that investment in regional climate adaptation would have significant benefits to agricultural production and food security (Willenbockel 2011, p. 35).

Fischer incorporates into the IIASA World Food Systems model two different General Circulation Models (HadCM3 and CSIRO) for climate projections for IPCC A2 emission pathways, running scenarios with and without CO2 fertilization. He runs the scenarios out to 2080, which is useful given the expectation of rising impacts over time. His model only includes rain-fed lands, which is a limitation. He draws three conclusions from his scenario runs (p. 111):

1. The regional impact of climate change is significant, posing threats to future food production.
2. There could be some improvements in rain-fed production if there is a positive CO2 fertilization effect and if farmers are able to adapt to changing climates.
3. The post-2050 scenario is particularly worrisome, as modeling shows increasingly negative and rapid impacts on production in most regions.

Fischer combines biofuel and climate change impacts for the different scenarios outlined earlier in the section on biofuels. If his pessimistic scenario (TAR-V1) is indeed the closest to the path we're now following, and if there is limited CO2 fertilization to moderate some climate change impacts, the prospects are dire. It shows cereals price impacts growing from 49% in 2020, to 53% in 2050 and up to 87% in 2080, though it is worth noting that his baseline for these changes assumes current climate conditions and no biofuel expansion.

Nelson, Rosegrant et al (2010) run a series of climate scenarios using IFPRI's IMPACT model. As with Fischer, the baseline is perfect mitigation, i.e., no change in the climate from 2010 forward. The simulations allow researchers to estimate the economic and social impacts of four climate scenarios of increasing intensity, defined as increasingly hotter and increasingly wetter. Using their "middle-of-the-road" assumptions of GDP and population growth from 2010 to 2050, they find that for the three main staple grains prices would rise between 20% and 32% more, averaging the four climate change scenarios, than they would in the baseline case of no climate change. As one would expect, the most intense climate scenario results in price increases 25-30% higher than that. Using their "middle of the road" assumptions, the researchers go on to estimate that compared to perfect mitigation the changing climate scenarios increase the number of malnourished children in 2050 by 8.5%-10.3%.

The authors make an interesting additional contribution, simulating an extended drought in South Asia (2030-35), which is one common climate forecast. This allows simulation of one aspect of climate change that is difficult for long-run modeling to predict – rising temperature variability and extreme weather events. The results show sharp price increases for all three of the major grains during the drought years, with a dramatic increase in the number of malnourished children.

Fuss, Havlik et al (2011) use the Global Biosphere Management Model (GLOBIOM) to assess the impacts on food security of yield uncertainty from climate change. If meeting minimum food needs is defined as a constraint of the model, and if yields are difficult to predict given the levels of uncertainty, what levels of production are required to ensure food security? They conclude that high levels of uncertainty about yields increase the need for decision-makers to plan levels of overproduction. They find this is feasible but potentially costly. They find that the key to success is the reduction of trade barriers to allow agricultural products to flow from surplus to deficit regions, and they find the most useful adaptation is the expansion of irrigation, which can help stabilize yields and expand production. They acknowledge that water use under climate change is inadequately accounted for in their model, so that adaptation strategy itself comes with significant uncertainties. Finally, they note the value of increasing global storage capacity for basic grains, as this reduces vulnerability to the kinds of short-term yield variations expected with climate change. This is one of the few mentions we found in the literature of the potential importance of food reserves in contributing to global food security in 2050 scenarios.

The Agricultural Modeling Improvement Project (AgMIP) is directly confronting the wide variability in climate-related simulations. As noted earlier, this involves comparing models by introducing common parameters and assumptions and imposing common scenarios. The differences allow cooperating modelers to identify the sources of outlying results, distinguish the effects of starting parameters versus modeling architecture, and improve efforts to model the many uncertainties associated with climate change impacts on agriculture.

The results across models are negative, a noteworthy change from previous rosier estimates of climate impacts on agriculture. While the AgMIP scenarios may be pessimistic in that they assume no CO2 fertilization, it remains striking that across a variety of GCM and crop models climate change lowers agricultural output. Differences among crop models are greater than differences caused by climate models, and this has a great deal to do with widely varying starting assumptions about demand, area, and yield growth. In their forthcoming article on the AgMIP climate modeling, Nelson, van der Mensbrugghe et al. (2013) highlight that "assumptions that are typically buried in technical reports can have significant effects on highly visible output measures." They call for this to be a high priority for further research, in addition to improving the reliability of agricultural data to fine-tune the crop models.

Most researchers also warn that the 2050 scenarios probably understate climate impacts because new scientific findings suggest the likelihood of greater disruptions to agriculture (Ackerman and Stanton 2013). Also, the effects of climate change are expected to be even more severe in the second half of the century. Those who have extended their projections to 2080 and beyond warn of growing impacts on agriculture after 2050 (e.g., Fischer 2011).

Scenario Modeling of Key Natural Resources

Modeling of key natural resources, particularly land and water, are also important to review. These biophysical models look less at economic characteristics such as supply, demand, and price but rather focus on trends in resource use based on biophysical data and interactions. Outputs are measured in biophysical units, such as land use. They often provide the biophysical parameter for economic modeling. Here we review briefly some of the noteworthy modeling of land and water resources.

Land

As noted earlier, land use is treated in differing ways in the modeling reviewed to this point. In most economic models, available agricultural land is identified through relevant biophysical modeling, such as GAEZ for the FAO assessment. The conversion of new land to agricultural uses is then one of the outputs driven by model as the equilibrium is established between supply and demand. In the case of the FAO model, 70 million hectares of additional agricultural land is required, an increase of 9%. Assumptions about land availability can be key to the results for other variables. For example, placing a modeling constraint on the expansion of agricultural land will produce much greater supply and demand imbalances and higher agricultural prices.

Ausubel, Wernick, et al. (2012), for example, employ their land use model to project the pressures on uncultivated lands from the demands of a growing population and changing diets. Their findings are relevant to the discussion of feeding the world in 2050 in part because they come to their conclusions from different parameters than do the socio-economic models. Their conclusion is, interestingly, cautiously optimistic. They suggest that we may be nearing the point of "peak farmland." This would mean that so-called "land sparing" – the extent to which uncultivated land remains in forest or other states – could actually increase by 2050. As such, existing resources could be adequate to fulfill future food needs. Their findings are cautionary because they note the "wild card" of global biofuels production as a factor that will have great influence on such a scenario; in fact, it already has in their model, interrupting global agricultural land-use trends.

Wirsenius, Azar, et al. (2010) illustrate what can be done by incorporating FAO economic modeling into biophysical "what if" scenarios. They start with the FAO baseline, which suggests that by 2030 global agricultural area will expand from the current 5.1 billion ha to 5.4 billion ha. They then model four scenarios for their impacts on land use. Faster growth in livestock production efficiency (basically feed efficiency) reduces land use from 5.4 billion to 4.8 billion ha. A 20% shift from beef to less land-intensive pork and poultry reduces that further, to 4.4 billion ha. Finally, they estimate another 15% reduction in the world's wealthier regions from a broader shift to diets relying less on meat and from reductions in food waste.

In a similar way, Tilman, Balzer et al. (2011) take global food demand estimates and model the implications for land use of intensification and extensification scenarios. They find that meeting global food demand by bringing more land into production (extensification) would result in one billion more hectares of land being cleared by 2050, with high levels of greenhouse gas emissions and nitrogen use. By contrast, the scenario of moderate intensification of production in low-productivity regions would reduce land demands by 80%, cut emissions by two-thirds, and slightly reduce global nitrogen use.

Water

The Comprehensive Assessment of Water Management in Agriculture (CAWMA) is a good recent example of attempts to integrate biophysical and economic information for policy-relevant scenario assessment (de Fraiture, Wichelns et al. 2007). The model relies on IMPACT for food demand and supply, and uses WATERSIM to simulate the same for water. They start with estimated crop demand to 2050 and estimate that water use for such production will need to increase by 70%-90%. The goal is to model five "what if" scenarios to assess the impact of different possible approaches to investment in water resources on our ability to meet global agricultural water demands. Notably, climate change is not considered in this simulation in order to make the outputs comparable. As explained earlier, this makes the results less relevant as *forecasts* but more relevant to policy-makers because the results of different approaches are easily compared. Briefly, the five scenarios and their results:

1. "Rainfed Optimistic" – Assumes that economic and environmental costs of large-scale irrigation prompt no increase to 2050 in irrigated crop production, the development focus instead being improved water management by poor, rural smallholders. It is optimistic because the scenario assumes that 80% of yield gaps are closed. The result – water needs would be adequate to meet global agricultural demand.
2. "Rainfed Pessimistic" – Only 20% of rainfed yield gaps are closed, necessitating a 53% increased in rainfed cropland to meet food needs. This has high environmental costs, and many countries have to increase their food imports significantly. Food insecurity increases, to the highest level of any of the scenarios considered.
3. "Irrigation Expansion" – Assumes large investments in irrigation, particularly in Sub-Saharan Africa and Asia, to reduce food dependence. The cost is high – US$400 billion – and the 33% increase in irrigated area supplies less than one quarter of the expected rise in food demand. Food security improves for many, but this approach brings added pressure on freshwater resources, more than doubling the number of people suffering water scarcities to 2.6 billion in 2050.

4. "Irrigation Yield Improvement" – In this simulation, the priority is improved efficiency in the use of land and water. This closes 75%-80% of the yield gaps, expands irrigated cropland globally by 9%, meeting half the additional demand for food by 2050. It is not inexpensive – US$300 billion – and there is a 32% diversion of freshwater resources to agriculture.
5. "Trade" – A final scenario allows much of the rising demand for food to be met by trade, with relatively water-abundant grain producers – USA, Canada, Argentina, etc. – exporting greater volumes to water-deficient countries. This reduces water stresses, but many potential obstacles make the scenario less likely, among them affordability for less developed importing countries, high energy use in international trade, and government wariness of excessive import dependence.

The authors conclude with a normative scenario designed to highlight optimal water-resource investment. This is extremely useful, as the limitations are clear in each of the five simulations. The authors model a portfolio approach that recognizes that different strategies will make sense in different regions. For example, in Sub-Saharan Africa a dual approach is followed, with a significant expansion of irrigation for cash crops, while efficiency gains are pursued for smallholders on rainfed lands. Overall, the simulation has yield increases of 58% for cereals on rainfed lands based on a 31% improvement in water productivity, while irrigated agricultural yields rise 55% based on a 38% increase in water efficiency. Strong regulations limit environmental impacts, intensification limits additional demands for agricultural lands, and there is only a 13% increase in freshwater withdrawals for agricultural production in 2050.

Again, the value of such a detailed set of controlled simulations is that they allow policy-makers to assess the likely impacts of different approaches to a more narrowly defined challenge. One limitation of this study is that none of the scenarios represents a "business as usual" approach against which different alternatives could be compared. Another is that climate change impacts might well shift the priorities and outcomes for water investment.

Modeling broader questions

The number of questions policy-makers face as they contemplate the long-range future is much broader than the specific variables of agricultural productivity, biofuels expansion, and climate change. Key concerns include the extent to which developing countries adopt Western diets high in animal protein, the sustainability of continued reliance on large quantities of fossil-fuel-based inputs on large monoculture farms, the positive impact of reducing inequality in access to food, and the impact of high price volatility on agricultural production and distribution. Such questions do not lend themselves easily to global quantitative modeling, precisely because the range of variables is so high. Still, quantitative projections remain important even with such broad uncertainties, and modelers have sought to quantify such alternative paths.

Reilly and Willenbockel categorized these as "exploratory scenarios" designed to draw out defined "storylines" (see Reilly and Willenbockel 2010 for a more extensive summary, pp 3055-3057) Again, such exercises have the goal of charting broad societal pathways, quantifying some of the implications, and highlighting the key drivers of change. The Millennium Ecosystem Assessment (MA) is a good example (Carpenter, Pingali et al. 2005). The four scenarios and their main outputs can be summarized briefly:

1. "Global Orchestration" – characterized by global trade liberalization and cooperation as agriculture moves to large industrial production, with limited environmental management. The result is high global per capita calorie availability, with a 40% decrease in child hunger. But environmental damage is significant, with a projected loss of 50% of Sub-Saharan Africa's forested land.
2. "TechnoGarden" – with high technological development, low trade and investment barriers, and the internalization of many environmental externalities in the global North. Private investment transforms developing country agriculture through intensification, dramatically increasing production in Sub-Saharan Africa. Food production and hunger levels are similar to scenario one.
3. "Adapting Mosaic" – has greater local and regional diversity, as WTO negotiations and global climate talks fail. The results vary widely from region to region, and food production globally is much lower than the previous two scenarios.
4. "Order from Strength" – features high trade barriers, limited global cooperation, little attention to ecosystem management. Weak agricultural investment generates large cropland expansion, and climate change contributes to hunger and mass migration in Africa. Food output grows very slowly to 2050, while child malnutrition increases.

The researchers use the results to highlight the dangers of "reactive" versus "proactive" environmental management and of fractured versus coordinated global approaches to trade and economic cooperation. Interestingly, none of the scenarios presents a crisis of global food production, as production per capita increases in all four cases. Willenbockel (2009), in a review of the MA and of an International Energy Agency assessment of climate scenarios, points to the importance of the MA findings that: societies are stressing ecosystems; those at greatest risk are the rural poor; some of the poorest countries face the most difficult environmental challenges; and global leaders must integrate environmental sustainability through global cooperation.

Similarly, French researchers used the Agribiom model for the Agrimonde project to compare a business-as-usual scenario (high-growth industrial agriculture derived from the MA's Global Orchestration scenario) to one based on equity and agro-ecological intensification of agricultural production. Such modeling, in this case based not on economic factors but biomass, contrasts current paths with an optimal alternative path to explore the consequences of each. In both, it is assumed that the world produces enough food, the questions are how and at what cost? For Agrimonde, part of the answer is complete equity in which diets of 3,000 kilocalories are assumed for all people in all countries. They find that we can meet future food needs even if yield growth is slower due to a shift away from industrial agriculture and toward smaller scale farms using agro-ecological practices. The exercise also clarifies the perhaps-unwanted impacts of such a path. To achieve this hypothetical future, there would need to be a 39% increase in cropland to make up for low yield growth, though researchers point out it can come largely from pasture because we would rely less on meat-based diets. There would also need to be a stunning 740% increase in global food trade, as surplus regions supply deficit regions (Paillard, Treyer et al. 2011). There is not accounting for how food-deficit regions would afford such a dramatic increase in imports.

Erb, Haberle et al (2009) offer one of the more extensive efforts to model alternative scenarios. Like Agribiom, the model is not economic, based instead on the supply and demand for available biomass from crop and grazing land. They use FAO estimates for their baselines on population, economic growth, agricultural productivity growth, and land use. Climate change and bioenergy scenarios were modeled, as were the impacts or four different diets, from "western high meat" to relatively low meat-based diets. Livestock models ranged from intensive to humane to organic. Land use for crops was varied from the FAO's baseline of a 9% increase to a larger 19% increase. The result is an impressive but somewhat dizzying array of 72 different scenarios.

They synthesized the results to assess a "wholly organic" future and an intermediate scenario. They conclude that the present path (high meat, industrial production) is feasible but only with high conversion of new crop and pasture land (20% instead of the FAO's baseline of 9%) and intensification of production. The low-meat, organic scenario was also feasible, with similar land needs (for grains for human consumption instead of for the expansion of grazing for meat production). The impacts of climate change would depend a great deal on the unknown of CO2 fertilization.

Other interesting efforts in this regard include a detailed literature review on the evidence base for climate mitigation from organic agriculture (Azeez 2009). IFPRI modeled a scenario of a 50% reduction in meat demand to 2050, in developed countries then also in China and Brazil. Not surprisingly, the results show significant reductions in agricultural prices and in food insecurity measures, with the changes in China and Brazil having a greater impact (Rosegrant, Tokgoz et al. 2013, p. 98) As Van Dijk (2012) explains, through the IPCC a process is well underway to develop a coherent set of scenarios – Shared Socioeconomic Pathways (SSPs) – that can be used in a consistent way by researchers to generate comparable assessments.

Conclusions

We have provided a broad overview of the ways in which researchers have attempted to quantify our ability to feed the world in 2050. While this by no means represents an exhaustive review of the relevant literature, it does provide an understanding of the sources for many of the widely quoted estimates of global food needs in 2050. It should also provide reassurance that many of these numbers have not been pulled out of thin air, but rather they are based on relatively reliable data and careful modeling that attempts to integrate biophysical and economic trends and relationships. Our review suggests, however, that the levels of uncertainty in both areas and the sensitivity of long-range results to small variations in basic assumptions make any such results highly speculative. Harkening back to Reilly and Willenbockel, these should not be taken as forecasts. Unfortunately, that is often how they are presented, usually through no fault of the modelers themselves.

Overall, we would concur with Reilly and Willenbockel that we are not faced with Malthusian futures. Thus there is no need for the kind of alarmist productivism often occasioned by some of these projections. Such warnings fuel everything from large-scale land acquisitions, in the name of looming food scarcity, to the expansion of input-intensive industrial farming, despite the resource constraints that prompted IAASTD to call into question that development path.

In fact, the FAO's 2012 projections of 60% increases in agricultural supply and demand seem a good starting point for discussion. They can allay some of the worst fears that population growth and changing diets will overwhelm our ability to produce food, while at the same time acknowledging both the uncertainties in such projections and the known factors – particularly biofuels expansion and climate change – that have not yet been adequately considered.

Reilly and Willenbockel are particularly concerned with how researchers deal with these uncertainties, which are inherent in the food system as a complex socio-ecological system, particularly in light of trying to model to such a long-term horizon like 2050. They usefully distinguish three types of uncertainty: technical, methodological and epistemological. Technical uncertainty relates to the quality of data available. Methodological uncertainties arise from a lack of sufficient knowledge to create an adequate model with suitable structure and functional forms of behavioral equations. Epistemological uncertainties refer to models' completeness or ability to deal with changes in human behavior or values, randomness of nature, technological surprises and/or "black swan" events. (p 3050)

In an overview article on the AgMIP project, von Lampe, Willenbockel et al. (2013) offer more specific suggestions related to improving the quality and usefulness of the modeling itself. From their model inter-comparison, they synthesize four types of differences found in the modeling:

1. Parameters and assumptions that the literature suggests should be within a narrower range, e.g. the high agricultural productivity growth assumptions in some models, noted earlier.
2. Better economic data is needed to inform the models, e.g., to sensitive assumptions such as demand elasticities, or land use, as pointed out by Hertel earlier.
3. Better data is needed from other disciplines, especially on biophysical processes about which there remains great uncertainty.
4. Finally, there are uncertainties the authors write "will not be resolved by research within the foreseeable future," including such basic parameters as GDP growth.

They conclude with a call to use a range of assumptions and present a range of results from such modeling, in order for it to be useful to policy-makers. "Exploring the outcomes from a range of plausible drivers is essential, not least as these drivers in part depend on decisions on public policies and private investments."

Among the most useful drivers to model are those that are most susceptible to policy intervention. Beyond the predictive value of economic modeling, such research should help illuminate the consequences of policy and behavioral change. Biofuels scenario modeling, for example, has not received the attention it deserves given the importance of the issue to food production and resource use and given the prominent role of public policies in promoting (or potentially discouraging) such use.

Perhaps even more striking is the absence in most of the modeling of the impacts of reductions in food loss and waste, which prevent an estimated one-third of food from nourishing anyone (FAO 2011). Many of the policy tools are certain, such as improved storage and infrastructure in developing countries and standards and public education to reduce retail and consumer waste in developed countries. The FAO is actively campaigning on this issue. Surely those who warn of looming food shortages in 2050 can develop clear scenario modeling to estimate the impact of, for example, a ten percentage point reduction in food loss by 2050. Under such a scenario, the FAO's baseline estimate of 2050 agricultural needs might drop again, from 60% to 50%. Kummu, de Moel et al (2012) estimate, for example, that reducing loss and waste to levels that are currently achievable could cut losses in half and provide enough additional food for one billion people.

This review suggests the following conclusions regarding further modeling that can help address key decisions facing policy-makers:

- **Global estimates are useful, but national and regional figures are far more instructive.** As noted earlier, there is no "we" who feed "the world." Global adequacy of projected food supplies can hide a plethora of inadequacies at the regional, national, and local levels. This will be all the more true as climate change impacts agricultural systems, with many of the poorest regions expected to be hit the hardest. While trade will be essential to addressing shortfalls, it would be a mistake not to assess regional food production capacities and focus on closing yield gaps, as many researchers have suggested.
- **Public and private investment in developing country agricultural productivity is a top priority.** We have seen how sensitive future food supplies are to increases and decreases in agricultural productivity. While it would be helpful if modelers could improve the quality and consistency of data they use in their projections, we do not need to wait for those projections to invest in developing country agriculture.
- **The priorities that should guide those investments are less a modeling question than a public policy question.** As the CAWMA project on water investments suggested, a portfolio approach tailored to the specific needs of a given region will be optimal for maximizing productivity within given resource

constraints. The same will be true for other agriculture-related investments. As Hillebrand's pessimistic "trend growth" scenario suggests, failing to raise productivity and food security in the regions that have been left behind will have dire consequences for the world's poor. Some of the normative modeling – Agrimonde, Millennium Ecosystem Assessment, etc. – offers a clear warning about paths that are not proactive on ecosystem management or cooperative in economic and environmental policy.

- **Modeling is likely to offer only limited guidance on the need for a transition to more sustainable methods.** We have seen how alarmist projections can lead to reflexive investment in large-scale industrial agriculture. Yet long-term resource constraints extend to many of the fossil-fuel-based inputs on which such systems depend. Normative modeling suggests that the environmental costs of such an approach are high, yet lower-yield agro-ecological methods would demand unsustainable tracts of new agricultural land to meet global food needs. Global long-range modeling will provide less guidance in such matters than a focus on scaling up proven strategies for the sustainable intensification of food production.
- **Uncertainties related to climate change are a particular challenge for modelers.** The AgMIP effort is a worthy and important attempt to improve modeling and increase the value of that modeling for assessing climate change. Uncertainties will inevitably remain, of course, making it incumbent on researchers to present their results transparently regarding the levels of uncertainty. Basic modeling parameters, however, need to be established so that the most widely quoted studies on feeding the world in 2050, such as from the FAO, include some accounting for climate change.
- **2050 is too short a time horizon to assess long-term sustainability.** As noted earlier, climate change and related resource constraints will have increasing impacts over the course of this century. Most models project far greater disruption to agricultural production after 2050 than before. Long-term modeling needs to account for this. Perhaps more important, given the difficulties of modeling to such a distant time horizon, policy-makers need to recognize that 2050 estimates may well be optimistic.
- **Long-range economic modeling generally minimizes the impacts of volatility, as supply and demand resolve within the models.** Yet we anticipate a future of increased volatility in the weather, affecting agricultural systems, and in agricultural markets, thanks to thin reserves and increasing financial speculation. More attention is needed to incorporate volatility into global long-range economic modeling (see Munier 2012, for example) .
- **Uncertainties about biofuels expansion should be less challenging and the area deserves more focused attention.** As we've seen, first generation biofuels expansion competes directly and indirectly for crops and resources, exerting upward pressure on food prices. Second generation biofuels should exert less pressure, but uncertainties remain. Meanwhile, most economic models to date have failed to take into account the likely and possible pathways for first generation biofuel expansion. To the extent such markets are driven by consumption mandates and other public policies, it is incumbent on modelers to represent the costs of such policies in their long-range projections. To date, they

haven't. Fischer's excellent scenario work with the IIASA model is now out of date, and subsequent efforts still rely on unfounded assumptions about possible biofuels paths. AgMIP's attention to the impact of advanced biofuels after 2030 is helpful, but it begs the more important question facing policy-makers: Can we feed the world if we are simultaneously feeding our vehicles from the same crops and lands?

- **Other direct contributors to supply and demand imbalances deserve prominent attention.** This need not come from economic modelers, but it could. Reductions in food waste – farm-to-market as well as at the retail and consumer levels – can have a direct impact on the accessible supply of food. An estimated one-third of food is lost or wasted (FAO 2011). Obviously, reducing such losses would make a great deal more food available for consumption while reducing resource use. It is striking that the principal economic models reviewed here do not model scenarios of even moderate food-loss reduction, which in developing countries would come primarily from improvements in storage and other infrastructure to reduce post-harvest and processing losses. This is, in itself, a valuable development goal.

Needs for future research

- **Biofuels scenarios, including public policy analysis:** Research needs to catch up to this very recent development, with careful modeling of both biofuels expansion scenarios and, to the extent possible, analysis of the impacts of consumption mandates and other public policies. Such research is important because, on the one hand, such policies may be critical to encouraging practices that undermine food security, while on the other, energy markets may well be more decisive in determining the expansion trajectories for biofuels. In the latter case, society may need to consider a different set of policies to regulate the impact of energy prices on food security.
- **The better integration of energy scenarios into agricultural modeling:** The long-term energy outlook has implications beyond biofuel expansion. It is directly relevant to the economic viability of high-input agriculture, reliant as it is on fossil-fuel-based inputs. If these rise in cost (or decline in availability), developing countries should be wary of agricultural development paths that increase their reliance on imported inputs. In other words, is IAASTD right that business-as-usual is not an option, and if so what is the alternative?
- **Climate change and its impacts on agriculture:** In addition to AgMIP's valuable initiative and the scientific community's ongoing efforts to improve our understanding of the impacts of global warming on our climate, there is a need for additional research on regional and crop-specific impacts, particularly in the developing world. Adaptation is local, and it needs to be guided by sound agricultural and economic analysis. Such research would focus less on global food provision and more on local strategies for climate-resilient agriculture.
- **Bringing stakeholders to the table:** Research should include a process to bring researchers into direct dialogue with the farmers who are on the frontlines of such

strategies and with developing country governments, which will be key to implementing them.

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