Public Sector Agricultural Research Priorities for Sustainable Food Security: Perspectives from Plausible Scenarios

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Introduction

There is widespread agreement that our ability to deliver sustainable food security for all will be challenged in three dimensions. First, population growth will continue through at least 2050 with almost all of the new mouths to feed living in today's developing countries, where expected higher incomes will mean growing demand for more food quantity and quality there, and the emergence of bio-energy may further add to demand for agricultural production. Second, the natural resource systems that provide food – water, soil, and biological resources – are already stressed in some parts of the world and will become increasingly so without careful attention to their sustainability. Finally, climate change will exacerbate the first two challenges.

Understanding the severity of these challenges, and what actions are needed to address them, requires an assessment of the magnitudes of the possible outcomes. The future is uncertain, but it is possible to construct a range of plausible futures, driven by a range of plausible drivers, including population and income growth and private sector agricultural research investments, to assess the future of sustainable food security. Using these same scenarios it is then possible to explore the consequences of a variety of public sector investments that could contribute to productivity and resilience. This report presents results for key indicators of sustainable food security from a set of scenarios that vary socioeconomic, agricultural productivity and climate change drivers, and then explores at an aggregate level the consequences of selected public sector agricultural productivity investments to improve human well-being.

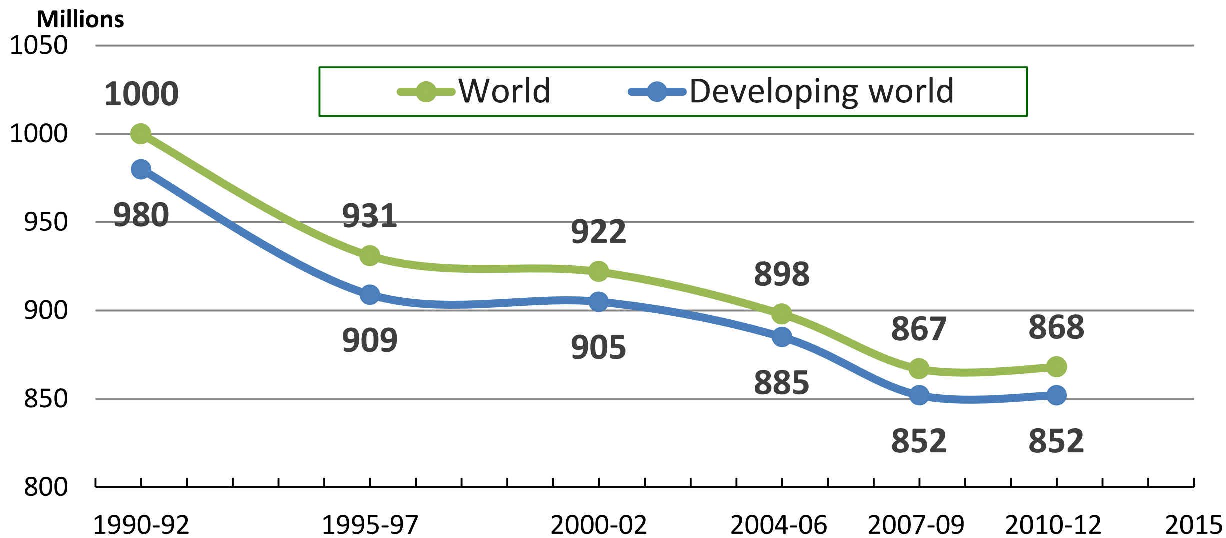
The report first provides an overview of current food security status and the results of recent assessments of the future of foods security by FAO and the CGIAR. This is followed by an overview of present and recent past history of research expenditures by the public and private sectors. Then the IMPACT suite of models is used with a range of set of plausible socioeconomic and biophysical drivers including climate change to explore the range of consequences for key outcomes in 2050.

The modeling tools are used to provide some initial assessments of the benefits of public sector agricultural research investments in new technology (biological and management).

The status of sustainable food security today

The latest FAO report on the State of Food Insecurity in the World (Food and Agriculture Organization of the United Nations 2012) estimates the number of under-nourished in the world at around 850 million persons (average over the period 2010-2012), based on a thorough revision of the estimation methodology. The revision did not change substantially the current estimate of the number of undernourished, but suggests better progress since 1990 as the revised estimate for 1990 of 980 million undernourished persons is substantially higher than the previous estimate of 833 million. It is still too early to judge the impact of the post-2006/07 food price rise on the number of under-nourished at the global level, but Figure 1 suggests that the period of relatively steady decline since 1990 was interrupted after 2007. These trends also suggest that the MDG1 hunger target is within reach at the global level, but more aggressive action will need to be implemented to reverse the apparent stall over the more recent years.

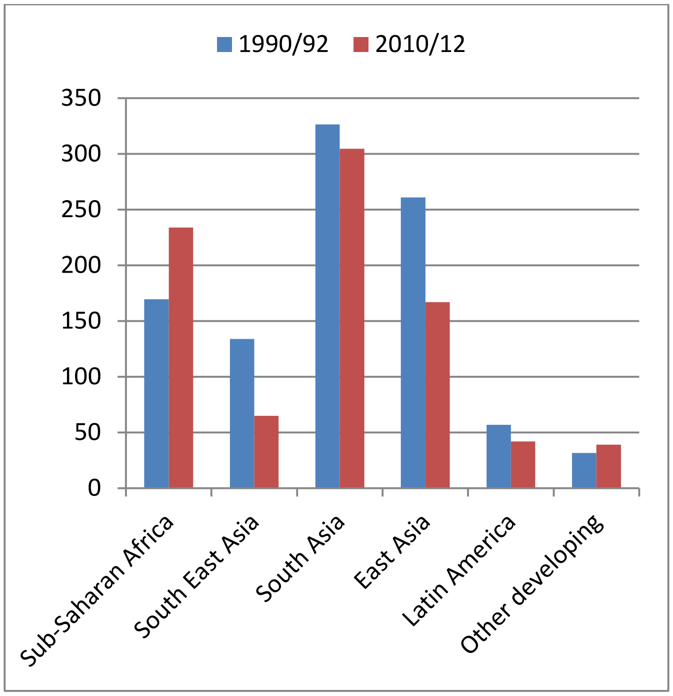
Figure 1. Undernourishment in the world



Source: Food and Agriculture Organization of the United Nations (2012).

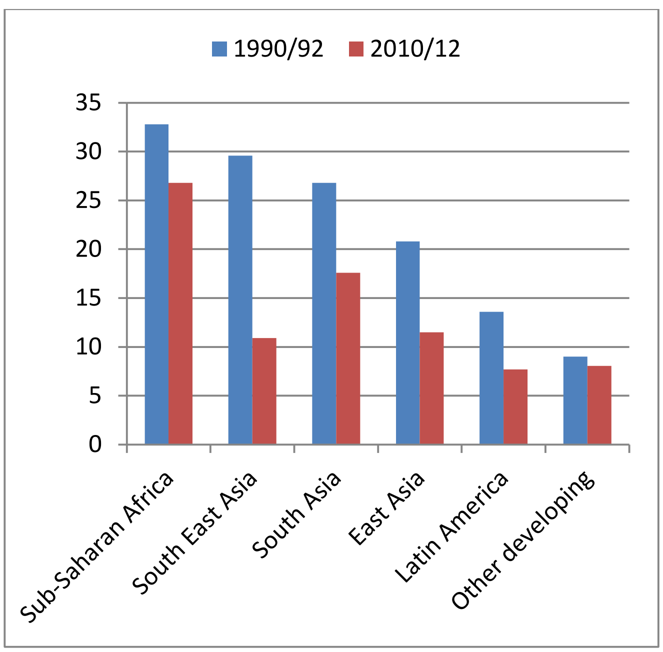
The global numbers also belie significant regional differences both in the current levels and the overall trends since 1990. As Figure 2 demonstrates, the largest concentrations of the undernourished are in South Asia (305 million), Sub Saharan Africa (234 million) and East Asia (167 million). In percentage terms, however, Sub-Saharan Africa outstrips all other regions with nearly 27 percent of its population estimated to be undernourished (Figure 3). South-East Asia as a region has made the most progress since 1990/92 with a 63 percent decline in the incidence of undernourishment. East Asia and Latin America are close to achieving a halving of the undernourishment index. South Asia has seen a drop of roughly 1/3 in the incidence of undernourishment. In Sub-Saharan Africa the decline has not even attained 20 percent. Note that Sub-Saharan Africa observed virtually stagnant growth throughout the 1990s.

Figure 2. Number of undernourished by major region (millions)



Source: Food and Agriculture Organization of the United Nations (2012).

Figure 3. Share of population undernourished by major region (percent)



Source: Food and Agriculture Organization of the United Nations (2012).

These estimates only reflect part of a complex story as they are based on calorie availability and not other indicators of undernourishment such as micro nutrients and proteins. They also reflect relatively long-term averages and do not measure the impact of episodic undernourishment and short-term price volatility.

The sources of food security challenges: drivers of change

The challenges to sustainable food security come both from the demand side – the number of people, their command over financial and physical resources, their dietary desires, and their location – and the supply side – the capacity of natural resources augmented by human actions where they are located to meet these demands over an extended period. The private sector, ranging from the smallest of small holder to the largest of global agribusinesses, manages these resources to meet their own internal imperatives of subsistence, survival and profitability. Ideally the public sector provides a 'level playing field' – the set of formal institutions that all participants are legally obliged to adhere to – as well as provision of various kinds of public goods that improve the workings of the private sector. Civil society watches over both the public and private sectors and uses its voice to improve the functioning of both.

All forward-looking scenarios start on the demand side with some assessment of population and income growth, and where the growth takes place, as they are key demand drivers for food security. Over the last few decades there have been a number of efforts to more closely link the economic and population scenarios into coherent storylines that also incorporate the supply side. Recent examples include the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005) and GEO5 (UNEP 2012).

In a somewhat different context, researchers working with the Intergovernmental Panel on Climate Change (IPCC) have periodically developed and released a common set of socio-economic scenarios that have storylines more focused on emissions profiles than on development paths per se—for example continued reliance on fossil fuels versus rapid transition to cleaner energy technologies. The most widely used of the IPCC scenarios were released towards the end of the 1990s and are commonly called the SRES scenarios (Nakicenovic et al. 2000). These became the mainstay of climate change research for the last 20 years. The IPCC's Fifth Assessment Report (AR5), to be released in 2014, is based on the parallel development of climate and socio-economic scenarios. The new climate scenarios focus on four emission pathways through 2100 with the measure of radiative forcing (watts/square meter (w/m^2)) in 2100 used to identify them; RCP2.6, a low climate change scenario that limits radiative forcing to 2.6 w/m^2 (the world is close to that limit now), RCP4.5, RCP6.0 and RCP8.5. The RCP climate scenarios were chosen as covering a plausible range of emissions pathways over the current century with enough variation to be able to differentiate the climate impacts.

In parallel, various teams have prepared socio-economic scenarios called shared-socio economic pathways (SSPs) (Kriegler et al. 2012; Moss et al. 2010; van Vuuren et al. 2012) that could be loosely combined with the climate scenarios. These scenarios have been motivated along two axes – highlighting mitigation and adaptation challenges. Table 1 provides an overview of the storylines of the five SSPs. For this report, we utilize the population and GDP quantifications for SSP2 and SSP3.

Table 1. The SSP storylines

Scenario	Mitigation challenge	Adaptation challenge	Description
SSP1—Sustainability	Low	Low	A world with relatively balanced growth, income disparities decline within and across countries, rapid technological progress particularly in the development of new and cleaner energy technologies, consumers are more attuned to the sustainability of their consumption behavior, rapid achievement of the Millennium Development Goals (MDGs) and thus populations are more capable of dealing with residual climate impacts.
SSP2—Trends as usual	Med	Med	Uneven growth—particularly within developing regions and slow convergence in incomes, some improvement in the carbon intensity of energy use, uneven achievement of the MDGs, muddling through with existing global governance structure.
SSP3—Fragmentation	High	High	Slow growth—particularly within developing regions, world trade and governance system falters, world becomes more regionalized, energy self-sufficiency becomes a primary objective, reductions in transfers of knowledge and capital, more reliance therefore on existing but carbon intensive regional energy supplies, large pockets of population mired in poverty with poor health and education achievements, hence high climate signal as well as populations with low capacity to adapt to ensuing climate impacts.
SSP4—Unequal world	Low	High	A world divided into two with a small group of wealthy elites—in both developed and developing worlds, that are by and large still using carbon intensive growth, but investing in clean technologies as a hedging strategy. Thus the mitigation challenge is relative low as the technologies are relatively easy to deploy, but the adaptation challenge is potentially high and the capacity of a large share of the population to adapt is low.
SSP5—Conventional development	High	Low	A world with high and relatively equal growth, MDGs are attained early, but development very much based on the previous 150 years, i.e. relatively carbon intensive and not much investment in cleaner technologies. Thus this scenario has a high climate signal, but with populations largely able to cope with the adaptation challenges.

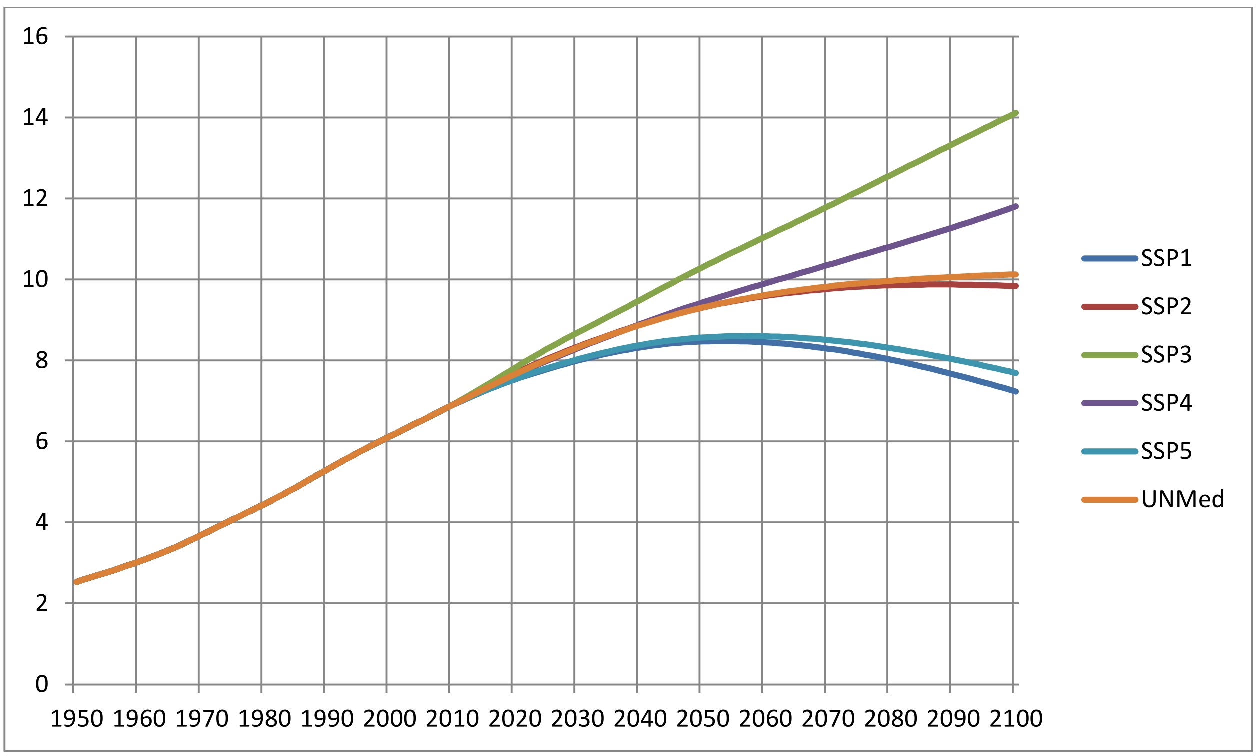
Source: O’Neill et al. (2011).

To estimate the magnitudes of the possible outcomes, these qualitative story lines must be converted into quantitative values. For the section below on AR5 scenarios, we use the OECD-based quantification of GDP growth and the population projections developed at IIASA for the SSP storylines.[1]

SSP population growth scenarios

Figure 4 shows global population from 1950 through 2100 under the five SSPs in Table 1 as well as the UN's medium variant from the 2010 revision. They result in potentially very different outcomes by 2100, though there is a narrower range of outcomes for our focus on 2050. Two of the scenarios have a relatively early peak and decline (SSP1 and SSP5) that could see global population decline towards current levels. Both SSP2 and the UN's medium variant have stabilization by 2100, at roughly 10 billion persons. SSP3 has potentially very dire impacts with a global population of around 14 billion by 2100 and continuing to increase.

Figure 4. Global population projection, various scenarios, billion



Source: UN Population Division (2010 Revision), IIASA and own calculations.

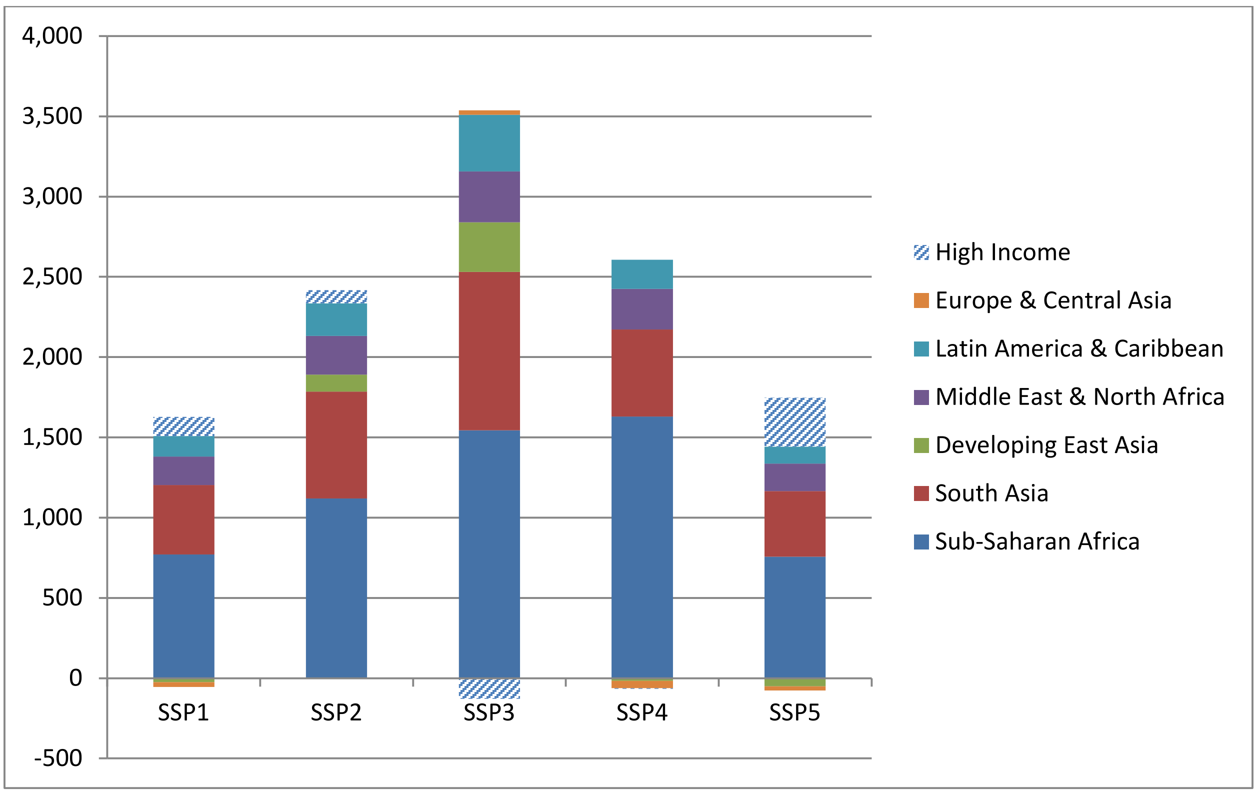
Focusing on 2050, the SSP2 and UN medium variant scenarios suggest that global population will increase by 2.4 billion between 2010 and 2050, smaller than the 1950-2000 increase of 4.4 billion. In percentage terms, the differences are much starker. Population growth in the fifty years from 1950 to 2000 was some 172 percent, but is expected to be only 35 percent over the 50 years between 2000 and 2050.

[1] IIASA/OECD, (2013). SSP Database (version 0.93). Accessed January 2013 at https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=welcome.

The trends for global population mask significant structural differences—under-15, working age, 65 and over, regionally and by educational attainment. We focus briefly on the regional differences, but the others have potentially significant economy-wide repercussions for example on labor force growth and food demand.

Figure 5 makes it clear that the bulk of population growth over the next 40 years will occur in two regions—Sub-Saharan Africa and South Asia. In the SSP2 scenario, these two regions account for about two thirds of the total growth in population. This outcome is a combination of relatively high base population and high population growth. The Middle East & North Africa region has a higher growth rate than South Asia overall, but from a lower base. For the other SSPs these patterns hold to some extent, but with some important regional differences. For example, under SSP3, the scenario with both high population growth and low economic growth, high-income countries see a decline in population (compared with a modest increase in SSP2). Under SSP5, on the other hand, the high-income countries would see a relatively robust increase in population.

Figure 5. Decomposition of population growth across broad regions between 2010 and 2050, million



Source: IIASA and own calculations.

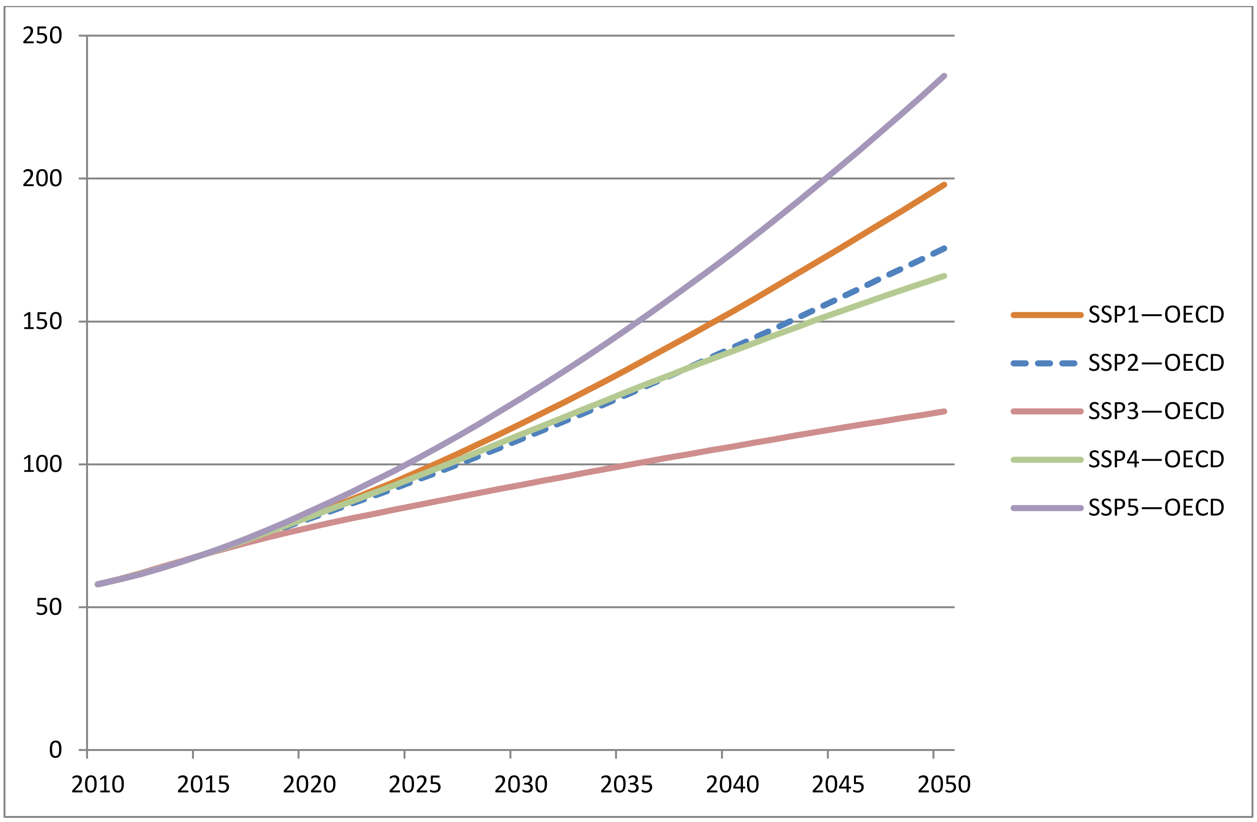
In some countries, today's children will witness revolutionary changes over the next 40 years if current trends are not reversed, regardless of scenario used. There are a handful of countries, most in Sub-Saharan Africa, that could see population increases of 200 percent or more. Examples include Niger, Zambia, Malawi, Tanzania, Angola, Burkina Faso, Somalia, Uganda and Mali. The need to cope with rapidly increasing populations will stress both natural and human resources. Some of the absolute increases are also stark, for example 415 million in India, 230 million in Nigeria, 130 million in Pakistan, 94 million in Tanzania, 82 million in Congo (DR), 62 million in Ethiopia and 61 million in Uganda.

To summarize, the world will need to find the resources to feed an extra 2.4 billion persons in 2050 under SSP2, and in even the lowest population growth scenario, the world's population is expected to increase by around 1.5 billion persons by 2050. The bulk of the population increase will be in two regions—Sub-Saharan Africa and South Asia. The former may have the natural resources (land and water) at the continental scale to help feed its incremental population—though with the need for significant financial resources to tap the unexploited potential and the danger of unsustainable use of those resources. South Asia could face a potentially more difficult problem in a region already stretching its natural resources and with climate change impacts rendering future agricultural production more uncertain.

Income growth scenarios

A second key component of forward looking scenarios is income growth. Figure 6 illustrates the range of potential outcomes for global income growth through 2050 for the OECD interpretation of the SSP storylines.

Figure 6. World GDP under various scenarios through 2050, $2007 trillion

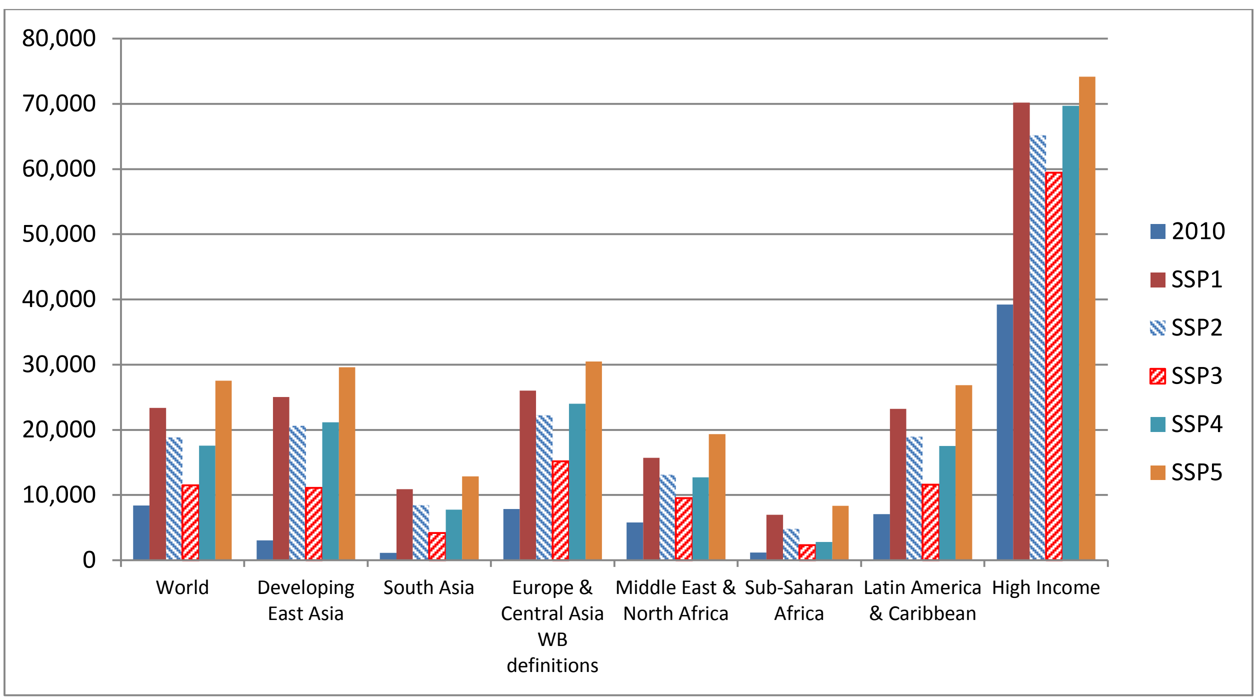


Source: IIASA, OECD and own calculations.

In 2010, global GDP was around $58 trillion[2]. The range of potential outcomes in 2050 is from a low of only $118 trillion for SSP3 to a high of $236 trillion for SSP5. In growth terms, this translates to about 1.8 percent per annum on average for the worst case scenario, to a high of 3.6 percent per annum in the best case scenario—a ratio of 2 to 1 in terms of growth rates. The SSP2 scenario has average annual growth of 3.26 percent.

Figure 7 depicts how the OECD SSP scenarios translate into per capita incomes in 2050—with the left-most bar in each group showing the 2010 starting point. At the global level, average income is $8,400 per capita in 2010. Under the worst scenario (SSP3), this would increase to only $11,500 by 2050; a truly miserable outcome should it obtain. The most optimistic scenario would see a rise to $27,500. These numbers are mirrored across the regions with rough symmetry—SSP1 and SSP5 framing the optimistic scenarios, SSP2 and SSP4 the intermediate scenarios and SSP3 the negative scenario. For the two poorest regions, the range in terms of potential outcomes is highest. Growth in Sub-Saharan Africa would vary from a low of 1.6 percent per annum per capita under the SSP3 scenario to a high of 5 percent under the SSP5 scenario. If SSP5 were continued over a 40 year period, that would put the region as a whole into a development pattern closer to those achieved by a number of East Asian countries. And if growth of 1.6 percent per annum is depressing, one could imagine worse—over a two-decade period starting in the 1980s, per capita income growth in Africa was essential zero. South Asia would benefit from a somewhat better outlook in relative terms, the range being between 3.3 and 6.2 percent per annum.

Figure 7. Per capita incomes under various scenarios, $2007 per capita



[2] All references to US dollars are to constant 2007 dollars.

Figure 7 also highlights that even in scenarios with considerable convergence, i.e. per capita growth rates much higher in the developing countries than in the high-income countries, income gaps remain large, with perhaps some exceptions, even when correcting for differences in purchasing power.

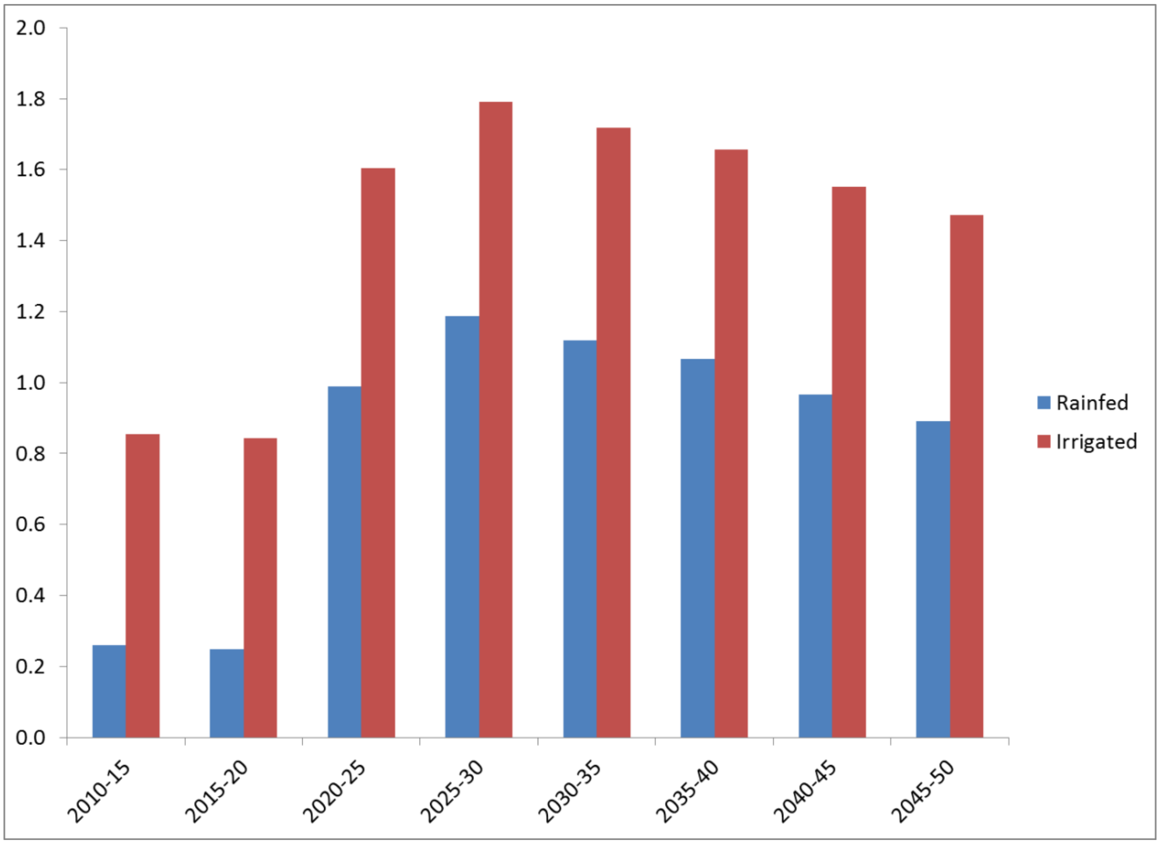
Agricultural productivity scenarios

Agricultural productivity is typically expressed in terms of units of useable output per unit of land, although water and solar radiation use efficiency are also important. Productivity increases on the farm can arise from changes in the genetic makeup of the crop produced by public and private sector researchers that take better advantage of farm level biophysical *and* socioeconomic conditions. Or they can be based on improved management practices, use and timing of inputs, and marketing of outputs. Research outputs are transferred to the farmer, either by the private sector or public sector outreach activities, along with the requisite knowledge of how to use them and the requisite inputs. In most dynamic agricultural sectors there is a two-way flow of information between farmers and researchers that increases the productivity of both.

Quantitative models typically include both exogenous and endogenous drivers of productivity change. Exogenous drivers are those productivity elements that arise outside the modeling environment. For example, private sector investments in agricultural productivity have become increasingly important, as indicated by the statistics in global trends on agricultural R&D investments below, but most models do not attempt to endogenize this behavior. Rather they include assumptions derived from expert judgments about plausible pathways for research and extension activities. Endogenous elements are typically those that respond to changes in input and output prices. Climate change impacts are additional to the exogenous effects from human activity.

For this report, we rely on the productivity drivers of the IMPACT suite of models, called intrinsic productivity growth rates, or IPRs. It is useful to describe how IMPACT deals with productivity increases that are outside of the direct modeling environment. For each crop in each spatial unit (called food production units or FPUs), and for both irrigated and rainfed management systems, IMPACT requires an assumption about IPRs in five-year increments. Figure 8 illustrates the concept with the IPRs for irrigated and rainfed rice in California. The IPRs were originally constructed based on empirical analysis of the determinants of yield growth in the 1990s (Evenson and Rosegrant 1995) and then updated as better information became available. As a general rule, with many exceptions, the IPRs tend to increase slightly over the next 10–15 years and then decline gradually (to 2050). This pattern is based on historical trends in research expenditures, as well as on expert opinion on how research expenditures are likely to continue and the effects on crop productivity. For this report, the IPRs do not include the effects of the increased funding for agricultural research since the mid 2000s. The exogenous IPRs are then adjusted to account for the effects of climate change.

Figure 8. Rice intrinsic productivity growth rates (IPRs) for the California FPU (exogenous yield increment, percent per year)



Source: Figure 20 in Nelson et al. (2010).

Table 2 describes the six scenarios used in a recent global model intercomparison exercise (see von Lampe et al. 2013). S1 and S2 assume that climate change does not occur and make it possible to isolate the effects of varying socioeconomic assumptions. S3 to S6 hold socioeconomic conditions constant and vary the climate change drivers, which are outputs from climate and crop models that use the most extreme of the AR5 climate scenarios RCP8.5 (see Moss et al. 2010 for a discussion of RCPs).[3] Table 3 reports the exogenous yield increases for selected crops (coarse grains, oil seeds, rice, sugar, and wheat) and countries (Brazil, Canada, China, India, and the USA). In the scenario without climate change (S1), the exogenous productivity increases between 2005 and 2050 range from 12 percent for oilseeds in

[3]RCP8.5 has a radiative forcing of over 8.5 watts per square meter, with a CO_2 concentration of about 935 ppm in 2100 compared to a level in the early 21st century of about 370 ppm. The global mean temperature (GMT) increase in 2050 (30-year average around 2050) is 2.4 and 2.2 for Hadley and IPSL respectively (the two GCMs used in this analysis), relative to 1980-2009. The 2-degree target widely used as an indicator of unsustainable temperature increase, starts from pre-industrial times, which was roughly 0.5° cooler than today. Using that time period, the GMT increase is 2.9 and 2.7 in 2050 (Personal communication from Christoph Mueller, PIK). In addition to using RCP8.5, the crop modeling assumes no CO_2 fertilization effect.

Canada to 132 percent for coarse grains in India. Across the countries included in Table 3, coarse grain (mostly maize) productivity increases are greatest and oilseeds the smallest.

Table 2. Climate change scenarios

Scenario identifier	Socioeconomic assumptions	General circulation model	Crop model
S1	SSP2	None	None
S2	SSP3	None	None
S3	SSP2	IPSL-CM5A-LR	LPJmL
S4	SSP2	HadGEM2-ES	LPJmL
S5	SSP2	IPSL-CM5A-LR	DSSAT
S6	SSP2	HadGEM2-ES	DSSAT

Notes: LPJml – Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model, DSSAT – Decision Support System for Agricultural Technology.

Table 3. Exogenous annual yield increases for selected countries, IMPACT model, 2005-2050 (percent per year)

Crop and commodity	S1	S3 – S1	S4 – S1	S5 – S1	S6 – S1
Coarse grains					
Brazil	2.23	-0.30	-0.15	-0.70	-0.68
Canada	2.19	-0.11	**0.12**	-0.23	-0.20
China	2.04	-0.13	-0.11	-0.53	-0.48
India	2.32	-0.20	-0.28	-0.72	-0.70
USA	1.68	-0.31	-0.20	-0.64	-0.82
Oil seeds					
Brazil	1.23	-0.42	-0.39	-0.27	-0.27
Canada	1.12	-0.12	-0.01	-0.10	-0.23
China	1.50	-0.09	-0.13	-0.06	-0.04
India	1.38	-0.37	-0.46	-0.20	-0.21
USA	1.43	-0.24	-0.18	-0.18	-0.26
Rice					
Brazil	1.48	-0.30	-0.24	-0.12	-0.19
China	1.43	-0.07	-0.06	**0.04**	**0.04**
India	1.79	-0.18	-0.23	-0.67	-0.61
USA	1.44	-0.11	-0.09	-0.01	-0.10
Sugar					
Brazil	1.71	**0.35**	**0.31**	-0.44	-0.40
Canada	1.69	**0.08**	**0.06**	**0.10**	-0.03
China	1.65	**0.09**	**0.08**	-0.28	-0.25
India	1.12	-0.14	-0.15	-0.54	-0.50
USA	1.32	**0.02**	**0.01**	-0.23	-0.32
Wheat					
Brazil	2.03	-0.43	-0.36	-0.70	-0.46
Canada	2.29	-0.09	**0.29**	-0.29	-0.05
China	1.62	**0.03**	-0.01	-0.37	-0.31
India	1.40	-0.20	-0.23	-0.58	-0.47
USA	1.49	-0.20	-0.14	-0.18	-0.20

Source: Nelson et al. (2013)

Notes: Positive effects of climate change are indicated in bold. The productivity effects reported here are exogenous to the modeling environment.

Climate effects on biophysical productivity are almost uniformly negative for the countries and commodities reported in Table 3, with the largest negative effects most often found on Brazilian and Indian crops. In a few cases, in the northern parts of the northern hemisphere (coarse grains in Canada

(S4), rice in China (S5 and S6), and wheat in Canada (S4) and China (S3)), climate change results in increased yields over the no-climate change exogenous effects. The exception to this general rule is sugar, where climate change increases yields in in S3 and S4 and in India in all scenarios.

Food security futures: FAO and CGIAR perspectives

FAO reports regularly on its institutional perspective of the future of food security (http://www.fao.org/docrep/016/ap106e/ap106e.pdf). The CGIAR does so on a more ad-hoc basis, principally through research publications on various food security topics by IFPRI. Starting in 2012, IFPRI began releasing an annual publication "Global Food Policy Report" that covers food security issues arising in the previous year (see http://www.ifpri.org/gfpr/2012 for the 2012 report).

FAO's Agriculture Towards 20xx Reports

Since the 1970s, FAO has regularly produced a number of reports on forward looking scenarios (these are the so-called AT20xx reports, where the AT means 'Agriculture Towards…'). Since their inception the AT reports have been highly detailed with global country-based coverage and many commodities. They are based on an accounting framework that insures global and sectoral consistency. But other than the accounting framework, the AT reports are largely based on expert information that loosely translates the exogenous drivers into demand and then production. Though based on a broad range of expert knowledge, the AT-style scenarios do not lend themselves to easy reproduction and/or sensitivity analysis.

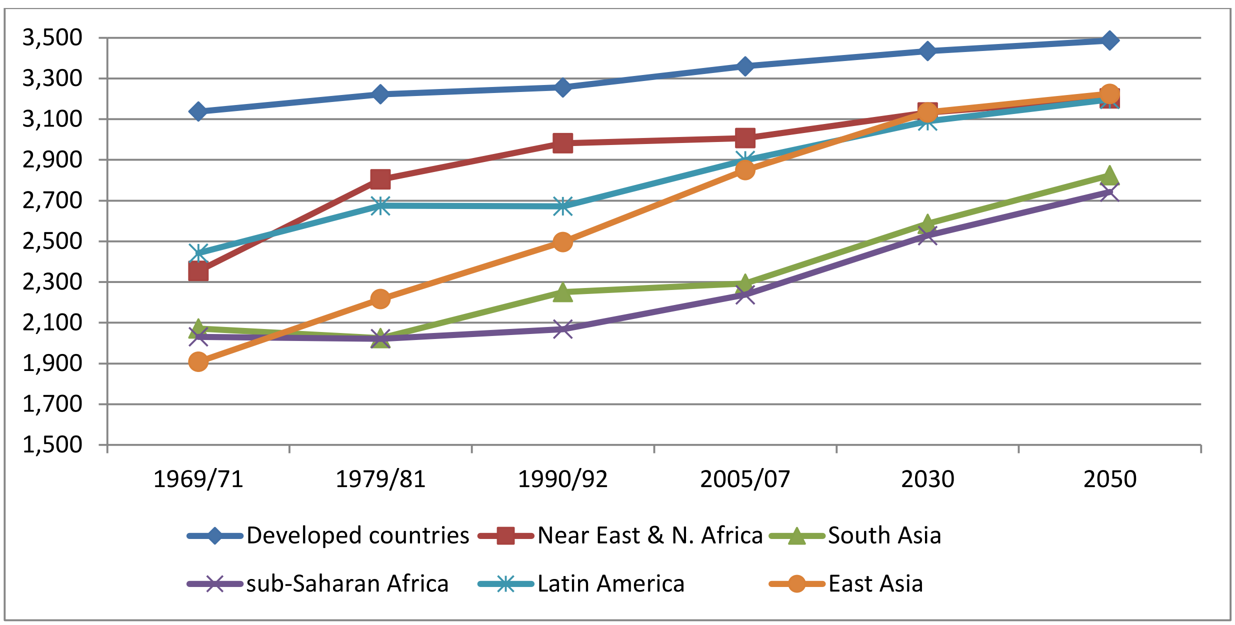
We report results from the 2012 version of the FAO's ATxx report. The drivers are somewhat different from the SSP2 drivers as it used the UN Population Division's 2008 revision and a somewhat dated World Bank scenario for income growth. The population differences between the 2008 and 2010 revision are not significant at the global level, but do make some difference at the regional level, particularly for Sub-Saharan Africa. The World Bank income scenario (AT/WB) is somewhat less optimistic than the OECD SSP2 income scenario. At the global level, the AT/WB scenario has annual GDP growth averaging 2.1 percent over the 2006/2050 period—compared to 2.8 percent under the SSP2 (OECD) scenario, and only somewhat better than the 1.8 percent of the pessimistic SSP3 scenario. Two regions have the highest differences—South Asia and Sub-Saharan Africa—and these are the two regions likely to have the highest income elasticities given their relatively low incomes. The annualized percentage differences are about 2 percentage points—that cumulatively will have large impacts over a 40-year time horizon. For the other regions on average, the differences are smaller and would have less impacts as these regions are relatively close to food saturation levels (or will be reaching these levels in the near future).

An important point to emphasize is that the AT reports in general and the 2012 update in particular ***do not*** include the productivity effects of climate change on agriculture. Hence, the results on production growth, yields, and other key variables do not reflect the negative effects of climate change indicated in Table 3.

The headline finding from the report is that agricultural production, weighted by base year prices, would increase by some 60 percent between 2006 and 2050 to meet anticipated demand (in a baseline scenario). The report assumes distribution neutrality and no specific policy changes in the future, and thus the number of undernourished, though declining, is still a feature of future food insecurity. Population growth alone would account for 39 percentage points of the increase in demand, with the remaining 21 percent due to income growth and whatever structural changes in the diet are linked to income growth. Caloric intake improves at the global level from some 2,772 kcal/day/person in 2006 to 3,070 in 2050 (an increase of 12.8 percent), and significantly more in the poorest regions; 2,240 to 2,740 kcal/day/person in Sub-Saharan Africa (22.3 percent) and 2,293 to 2,820 kcal/day/person in South Asia (23 percent) (Figure 9). Pockets of undernourishment would remain a high concern through 2050, but the incidence would be down to 4.1 percent in developing countries, from the estimated level of around 16 percent in 2006. With climate change effects considered, these outcomes are less positive.

These results assume no change in policies, but if targeted policies are pushed more actively—particularly in the most vulnerable countries and sub-regions, the report's authors suggest that a zero-hunger target should be achievable. There is a modest increase in trade, with developing countries on average somewhat more import dependent for cereals.

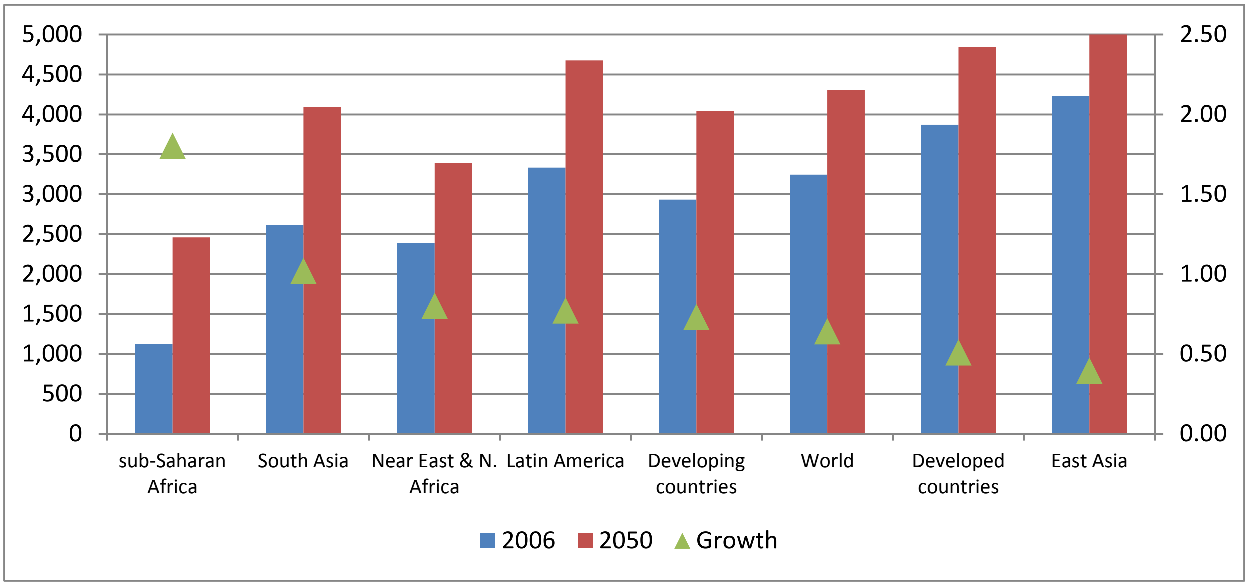
Figure 9. Possible caloric outcomes, kcal/day/person



Source: Alexandratos and Bruinsma (2012).

Yield growth accounts from some 80 percent of the overall production increase, with modest improvements in cropping intensity and land changes accounting for the residual. Figure 10 depicts the average yields for the standard regions aggregated over all cereals for the base year (average of 2005/07) and 2050. There is a great deal of variance across regions with very low yields on average in Sub-Saharan Africa (around 1100 kg/ha) to a high of over 4000 kg/ha in East Asia—even somewhat higher than in developed countries. The green triangles shows the projected yield growth rates across the regions (right-axis). The AT report assumes growth in yields of some 1.8 percent per annum in sub-Saharan Africa, perhaps on the optimistic side, though consistent with yield gap analysis. South Asia would see more modest growth of 1 percent, with slower growth in all other regions. At the world level, the implied yield growth is 0.64 percent per annum.

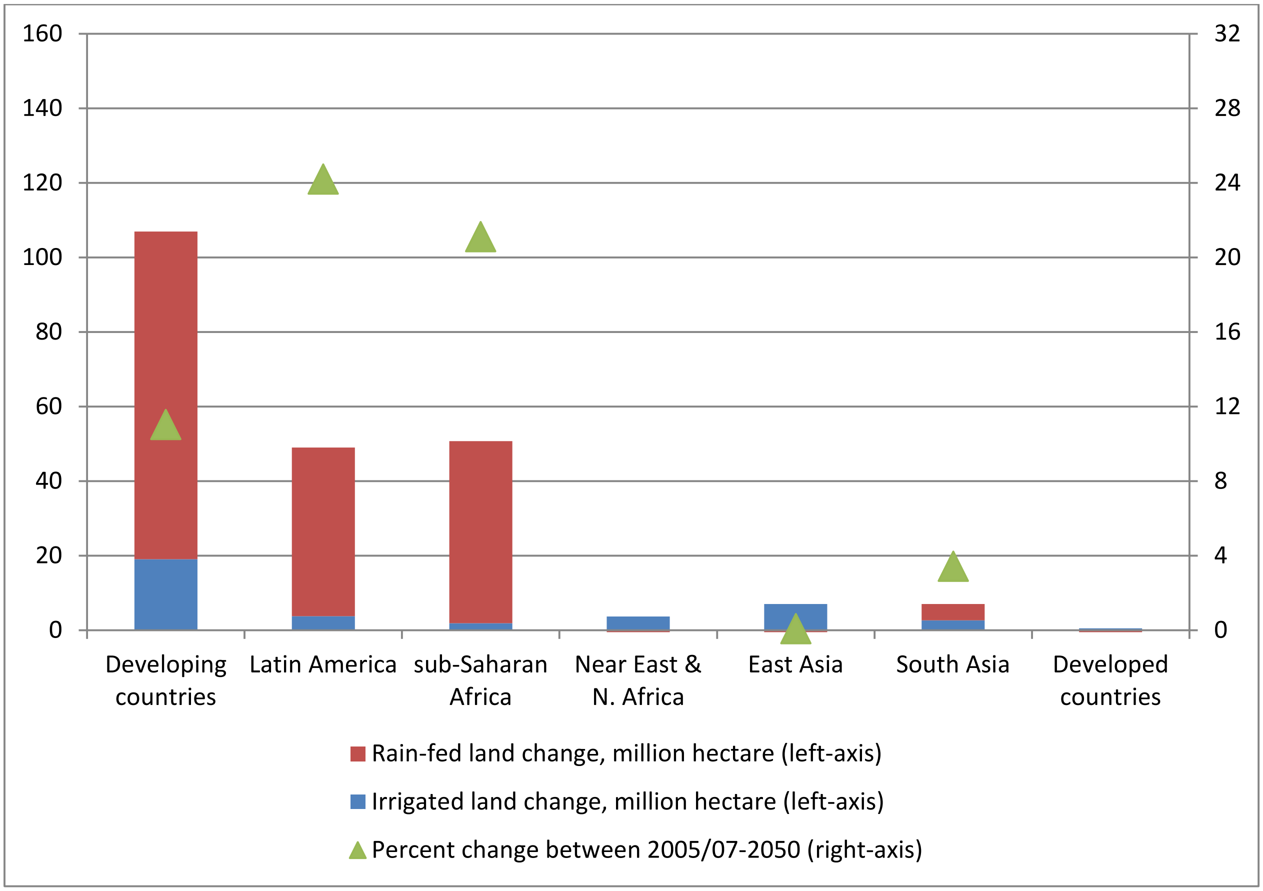
Figure 10. Modest yield improvements, with one exception (kg/ha left-axis, growth percent per annum right-axis).



Source: Alexandratos and Bruinsma (2012).

The implications for land use are provided in Figure 11. For most regions the land implications are modest both in absolute and relative terms. Two regions stand out—Latin America and sub-Saharan Africa. Each has an increase in land devoted to crops of 45 to 50 million hectares—little of which would be devoted to additional irrigated land. Some of the other regions would see some marginal increase in land under irrigation, but overall with very modest land use changes. Global land use would increase by around 70 million hectares—an increase of 107 million hectares in developing countries and a decline of some 38 million hectares in developed countries. Note, that in the AT scenarios, there is no incremental demand for bio-energy beyond the demand implied by existing biofuels mandates. More aggressive use of bio-energy would be expected to have an impact on these relatively modest land-use changes. A more modest improvement in yields—compared with the trends depicted above, could also lead to less pressure on land use. Finally, the AT report is predicated to some extent on minimal changes in net trade. In a more globalized world where stable access to food was assured, more open trade would enable some production shifts to regions that have a distinct comparative advantage.

Figure 11. Land use change, 2005/07 - 2050



Source: Alexandratos and Bruinsma (2012).

Highlights from the Food Security, Farming, and Climate Change to 2050 report

As mentioned above, the CGIAR does not publish regular assessments of food security futures. In this section, we report highlights from the IFPRI research monograph "Food Security, Farming, and Climate Change to 2050" (Nelson et al. 2010). This monograph uses the UN population growth scenarios combined with GDP scenarios developed based on earlier studies to construct three overall scenarios – optimistic, baseline, and pessimistic – each of which is combined with five different climate scenarios. The climate scenarios include one with perfect mitigation and therefore no climate change effects and four that reflect different combinations of general circulation model results and different SRES scenarios.

Unlike the ATxx results, the results in this section are from a partial equilibrium model with extensive spatial detail that endogenizes country-level production, consumption, trade flows and prices.

World prices are a useful indicator of the future of agriculture (see Table 4). Rising prices signal the existence of imbalances in supply and demand and growing resource scarcity, driven either by demand factors such as growing population and income, or by supply factors such as reduced productivity due to climate change. Unlike much of the 20th century, when real agricultural prices declined, this analysis suggests that real agricultural prices will likely increase substantially between now and 2050, as the result of growing incomes and population as well as the negative productivity effects of climate change. The likely price increase ranges from 31.2 percent for rice (in the optimistic scenario) to 100.7 percent for maize (in the baseline scenario). With perfect mitigation, these price increases would be less: from 18.4 percent for rice in the optimistic scenario to 34.1 percent for maize in the pessimistic scenario. These still-substantial increases reflect the relentless underlying pressures on the world food system, even in the unlikely event that perfect mitigation can be achieved (that is, all greenhouse gas emissions are halted and the inertia in the climate system can be overcome).

Table 4. Price outcomes of the overall scenarios and the simulations

Scenarios	Maize	Rice	Wheat	Maize	Rice	Wheat
	% price change, 2010 mean to 2050 mean *(2050 std. dev. and CoV[4])*			% price change, 2050 perfect mitigation to 2050 mean CC		
Baseline	100.7 *(24.6; 0.104)*	54.8 *(4.2; 0.011)*	54.2 *(14.0; 0.060)*	32.2	19.8	23.1
Optimistic	87.3 *(25.4; 0.114)*	31.2 *(2.0; 0.006)*	43.5 *(13.8; 0.063)*	33.1	18.4	23.4
Pessimistic	106.3 *(25.5; 0.109)*	78.1 *(4.3; 0.010)*	58.8 *(15.3; 0.065)*	34.1	19.5	24.4
Simulations with baseline scenario	% price change, 2010 mean to 2050 mean			% price change, 2050 perfect mitigation to 2050 mean CC		
Productivity improvement simulations						
Overall	59.8	31.2	20.0	36.2	20.0	22.2
Commercial maize	11.9	53.8	50.0	33.9	19.8	22.8
Developing country wheat	97.9	54.4	28.2	32.1	19.8	22.5
Developing country cassava	97.5	54.5	53.0	32.0	19.8	22.9
Irrigation	101.5	50.1	52.5	34.3	19.5	22.7
Simulation of drought in South Asia 2030–2035	93.7	55.0	51.9	31.8	19.8	22.9

Source: Table 7 in Nelson et al. (2010).

Note: The percentage increase for the scenarios is the mean across the results for the four climate scenarios, CSIRO and MIROC GCMs with the SRES A1B and B1 GHG forcings. For the overall scenarios, the numbers in parentheses and italics are the standard deviation (std. dev.) and coefficient of variation (CoV) of the 2050 price for

[4] The standard deviation shows how much variation a variable has from its mean value. A larger value means that the range of the variable—prices in this case—is also large. It is a useful summary value for variability in a single variable but cannot be used to compare variability of different variables. The coefficient of variation (CoV) is the standard deviation divided by the mean. It makes possible comparisons of the variability of different variables (for example, prices and the number of malnourished children).

the four climate scenarios. The perfect mitigation results assume all GHG emissions cease in 2000 and the climate momentum in the system is halted.

Domestic production combined with international trade flows determine domestic food availability; per capita income and domestic prices determine the ability of consumers to pay for that food. The average person in low-income developing countries today obtains only two-thirds of the calories available in developed countries (Table 5). With high per capita income growth and perfect climate mitigation, calorie availability in developing countries reaches almost 85 percent of the developed countries by 2050. And in the optimistic scenario, because the poorest countries grow more rapidly between now and 2050, they catch up to today's middle-income countries. With the pessimistic overall scenario, however, both calorie availability and general human well-being declines in *all* regions. Note that the changes in calorie available in Table 5 are substantially smaller than those reported by the 2012 FAO AT report, and if the pessimistic scenario developed, the calorie availability drops in all regions.

Table 5. Scenarios results for number of malnourished children and average daily kilocalorie availability

Scenarios	Number of malnourished children				Daily kilocalorie availability		
	% change 2010–2050	Increase in 2050 over perfect mitigation (%)	2050 std. dev.	2050 CoV	% change 2010–2050	2050 std. dev.	2050 CoV
Developing							
Baseline	-25.1	9.8	1,810	0.015	0.4	32.6	0.010
Optimistic	-45.9	10.3	1,667	0.020	4.7	36.9	0.011
Pessimistic	-1.8	8.7	9	0.014	-8.3	30.6	0.010
Low-income developing							
Baseline	-8.6	9.5	709	0.016	0.8	31.8	0.010
Optimistic	-36.6	11.5	657	0.022	9.7	36.9	0.011
Pessimistic	18.1	8.6	9	0.015	-6.2	30.1	0.010
Middle-income developing							
Baseline	-32.3	10.0	1,109	0.015	8.5	33.6	0.015
Optimistic	-49.9	9.6	1,010	0.018	34.6	45.8	0.016
Pessimistic	-10.3	8.7	9	0.013	-5.9	31.0	0.016

Source: Table 15 in Nelson et al. (2010).

Note: The standard deviation (std. dev.) and coefficient of variation (CoV) values are for the number of malnourished children and the daily kilocalorie availability in 2050.

Calorie availability is an important component in one metric of human well-being—the number of malnourished children under the age of five. This number captures some, but certainly not all, of the human suffering that can result from the combination of slow economic growth and climate change, coupled with inappropriate government policies. Overall, in the optimistic scenario, the number of malnourished children in developing countries falls by over 45 percent between 2010 and 2050 (Table 5). With the pessimistic scenario, on the other hand, that number only decreases by about 2 percent.

The benefits of the optimistic scenario are greatest for the *middle-income* developing countries, which have the greatest share of world population. For these countries, the optimistic scenario results in a 50-percent decline in the number of malnourished children; in the pessimistic scenario, that number still declines, but by only 10 percent. Under the optimistic scenario, *low-income* developing countries show a decline of 37 percent in the number of malnourished children—but the pessimistic scenario is devastating: the number of malnourished children *increases* by more 18 percent.

Climate change exacerbates the challenges in reducing the number of malnourished children, although the effects are mitigated by economic development. For all regions, the negative productivity effects of climate change reduce food availability and human well-being. Climate change results in even greater price increases by 2050 (Table 4). It causes an increase of between 8.5 and 10.3 percent in the number of malnourished children in all developing countries, relative to perfect mitigation (Table 5).

Despite large differences in precipitation amounts and seasonal variation across the climate scenarios, the differences in price and other outcomes under different climate change futures are relatively small. The exception is the dramatic effect on international trade flows (Table 6). Changes in developed country net cereal exports from 2010 to 2050 range from an *increase* of 5 million metric tons (mt) in the perfect mitigation scenario to a *decline* of almost 140 million mt. This is because the global scenarios that are wetter on average are particularly dry in the central United States, resulting in much lower 2050 maize and soybean production and therefore in reduced exports than the drier global scenarios

Trade flows can partially offset local climate change productivity effects, allowing regions of the world with positive (or less negative) effects to supply those with more negative effects. This important role for international trade can be seen in the results for a simulation of a South Asian drought, which models an extended drought beginning in 2030, with return to normal precipitation in 2040. Substantial increases in trade flows soften the blow to Indian consumers. During the drought the region sees large increases in imports (or reductions in net exports) of three key commodities, rice, wheat, and maize. These net imports drive world prices higher. Essentially, other countries' producers and consumers help to reduce, though certainly not eliminate, the human suffering that a South Asian drought would cause.

Table 6. International trade of maize, rice, and wheat

Commodity & category	2010 (mmt)	2050 % change	2010 (mmt)	2050 % change	2010 (mmt)	2050 % change
	Baseline		Pessimistic		Optimistic	
Developed						
Maize						
Perfect mitigation	36.7	120.5	37.5	127.1	37.2	105.8
Climate change mean	27.8	-25.4	27.7	-36.6	27.4	-56.9
Rice						
Perfect mitigation	-2.6	-20.5	-2.7	-61.8	-2.6	-13.7
Climate change mean	-3.0	-12.0	-3.1	-40.5	-3.0	-3.8
Wheat						
Perfect mitigation	44.6	-48.8	44.1	-37.2	44.5	-39.5
Climate change mean	42.7	-66.8	41.8	-61.8	42.2	-63.9
Middle-income developing						
Maize						
Perfect mitigation	-33.8	81.5	-33.8	83.0	-34.1	62.2
Climate change mean	-26.1	-59.4	-25.4	-80.6	-25.7	-98.0
Rice						
Perfect mitigation	-7.0	-65.7	-6.8	25.1	-7.0	-171.7
Climate change mean	-7.5	8.2	-7.3	82.2	-7.4	-94.9
Wheat						
Perfect mitigation	-38.7	-111.4	-38.1	-87.0	-37.2	-148.4
Climate change mean	-37.6	-121.5	-36.8	-104.2	-35.8	-161.7
Low-income developing						
Maize						
Perfect mitigation	-2.9	571.1	0.6	571.1	-3.1	586.3
Climate change mean	-1.7	506.0	0.5	506.0	-1.7	555.9
Rice						
Perfect mitigation	9.6	-53.4	-0.1	-53.4	9.6	-128.5
Climate change mean	10.4	2.5	0.0	2.5	10.4	-68.5
Wheat						
Perfect mitigation	-5.9	363.5	0.4	363.5	-7.3	516.3
Climate change mean	-5.1	337.8	0.3	337.8	-6.4	482.4

Source: Table 11 in Nelson et al. (2010).

Increases in agricultural production are essential to meeting the demand growth from population and income. While area expansion is still possible in some parts of the world, the possibility of negative environmental effects is substantial. Agricultural productivity investments make it possible to meet that increased demand from existing agricultural land resources, while reducing some of the environmental threats from increased production. This monograph looked at five different types of productivity enhancements: an overall increase in crop productivity in developing countries of 40 percent relative to our baseline assumptions; an increase in commercial maize productivity; improvements in wheat and cassava productivity (analyzed separately) in selected countries in the developing world; and an increase in irrigation efficiency (See Table 16 in Nelson et al. (2010)).

Not surprisingly, the overall productivity increase had the greatest effect on human well-being, reducing the number of malnourished children in 2050 by 16.2 percent (or 19.1 million children under 5) relative to the baseline result. Some in the commercial maize industry suggest that commercial maize yields can increase by an annual average of 2.5 percent through at least 2030, so the monograph simulated a 2 percent increase through 2050. This productivity change would affect about 80 percent of world production in 2010. The effects on world maize prices are dramatic: prices increase only 12 percent, instead of 101 percent, between 2010 and 2050. The effect on malnourished children is also not insignificant, with a 3.2 percent decline relative to the baseline in 2050. The effect is larger in the low-income developing countries (a decline of 4.8 percent) because maize consumption is relatively more important in this group of countries.

The wheat productivity experiment increases productivity to 2 percent in selected developing countries that together account for about 40 percent of world production in 2010. Because less production is affected than in the maize simulation, the outcomes for human well-being are less dramatic, with only a 2.2 percent reduction in the number of malnourished children in developing countries in 2050 (Table 23 in Nelson et al. (2010)). The middle-income developing countries fare better (a 2.5 percent reduction) than the low-income developing countries (1.6 percent reduction), because India and China are both major wheat producers and consumers and are included in the group of middle-income developing countries.

Cassava is a particularly important crop for consumers in some low-income developing countries. It is the fourth most important source of calories for this group of countries and provides about 8 percent of average daily consumption. The simulation increases productivity to 2 percent annually for the six top producing countries (Brazil, the Democratic Republic of Congo, Ghana, Nigeria, Indonesia, and Thailand) that collectively accounted for over 60 percent of world production in 2000. While the effect on the number of malnourished children is only a 1.1 decline in 2050 for all developing countries, it is concentrated in the low-income developing countries, where the decline is 2.2 percent (Table 25 in Nelson et al. (2010)).

Finally, we looked at the effects of a 15 percent increase in irrigation efficiency in developing countries. The world's irrigated area is concentrated in South and East Asia. In East Asia, increased precipitation from climate change (in most scenarios), along with changing consumer preferences away from rice, reduce the need for irrigated area between 2010 and 2050. Therefore, any irrigation efficiency improvements there have relatively small effects on food production (although they are critical for freeing up water for industrial and urban use). In South Asia, however, the benefits of more efficient irrigation are substantial. And for middle income countries as a whole, increased irrigation efficiency reduces the number of malnourished children in 2050 by 0.3 percent, or about 0.3 million children (Table 34 in in Nelson et al. (2010)). In low-income developing countries, however, because the share of irrigated area is low, the efficiency effect is small, reducing the number of malnourished children by only 0.2 percent (0.1 million children).[5]

Results from the AR5 scenarios

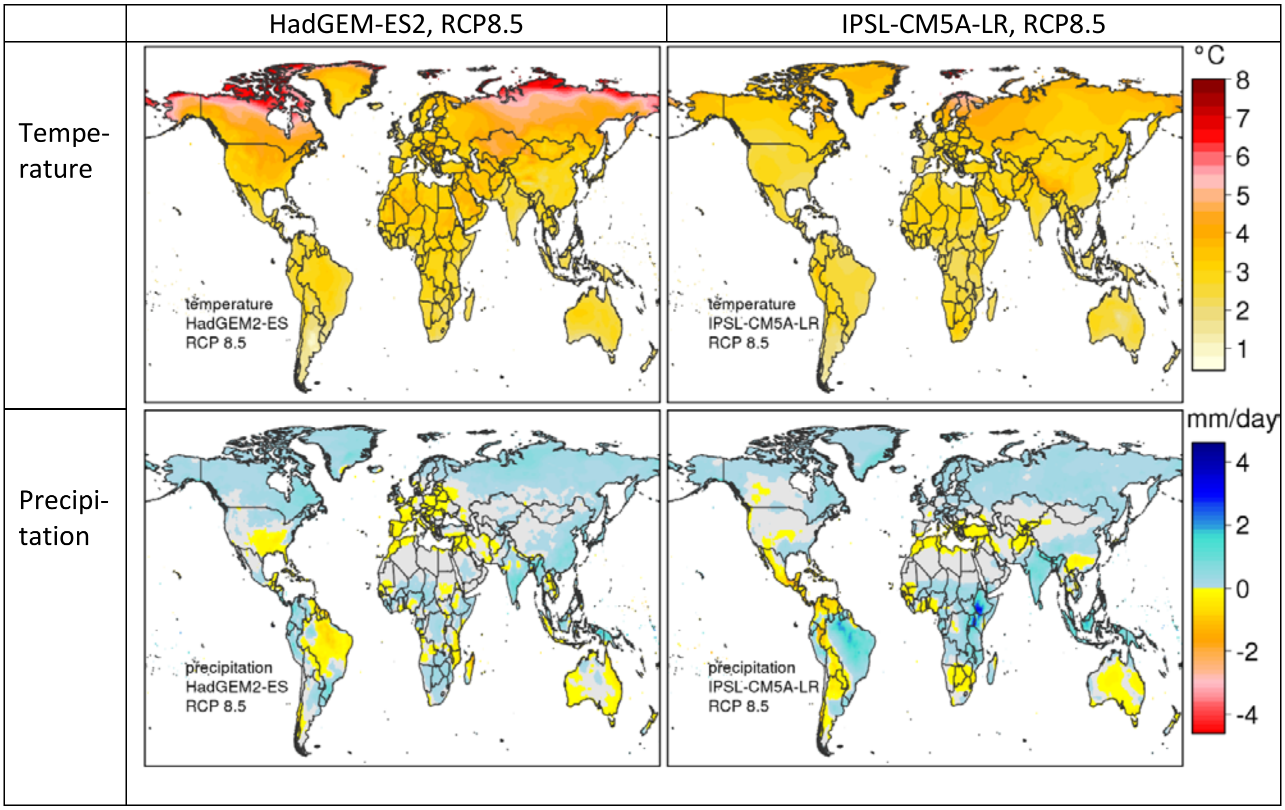
In this section we report selected results from the scenarios developed for the AgMIP Global Economic Model Intercomparison exercise. For the most part the results reported here are from the IMPACT suite of models but we provide comparative results on price changes from other models.

To assess differences in climate change modeling, data from scenarios with four climate-change related productivity effects were used (S3-S6, see Table 2) based on the most extreme of the Representative Concentration Pathways (RCPs) developed for AR5. The RCP data are used as an input into two general circulation models (GCMs) – Hadley and IPSL. The resulting climate outputs were bias-corrected and downscaled for the ISI-MIP model comparison project (http://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/research/rd2-cross-cutting-activities/isi-mip). The ISI-MIP climate data were then used as inputs into two crop growth models – the Lund-Potsdam-Jena model of the managed planetary land surface (LPJmL) (Bondeau et al. 2007) and the suite of crop models included in the Decision Support System for Agricultural Technology (DSSAT) software (Jones et al. 2003). Climate data for 2000 and 2050 were used to generate yields at ½ degree resolution (about 55.5 kilometers at the equator). The crop modeling assumed a limited CO_2 fertilization effect in 2050, using a CO_2 concentration level of 370 ppm in 2050, roughly the level in 2000. CO_2 fertilization is especially important for crops such as rice, oil seeds, and wheat that use the C3 photosynthetic pathway and can partially offset the negative effects of higher temperatures and precipitation. The combination of the most extreme RCP outputs with an assumed low CO_2 concentration level in 2050 means that the negative productivity effects are at the upper end of what is plausible by 2050.

Figure 12 displays changes in temperature and precipitation for the two GCMs using the RCP8.5 drivers. The Hadley model has slightly higher average temperatures with significantly greater increases in the far northern latitudes than the IPSL model. The Hadley model has substantial drying in the southeast of the U.S. and the Amazon region while the IPSL model has precipitation increases in those locations.

[5] The results reported here aggregate country-specific outcomes which can be quite diverse. For country-specific results in sub-Saharan Africa, three research monographs based on the findings in Nelson et al. (2010) (Jalloh et al. 2013; Waithaka et al. 2013; Hachigonta et al. 2013) will be released in 2013.

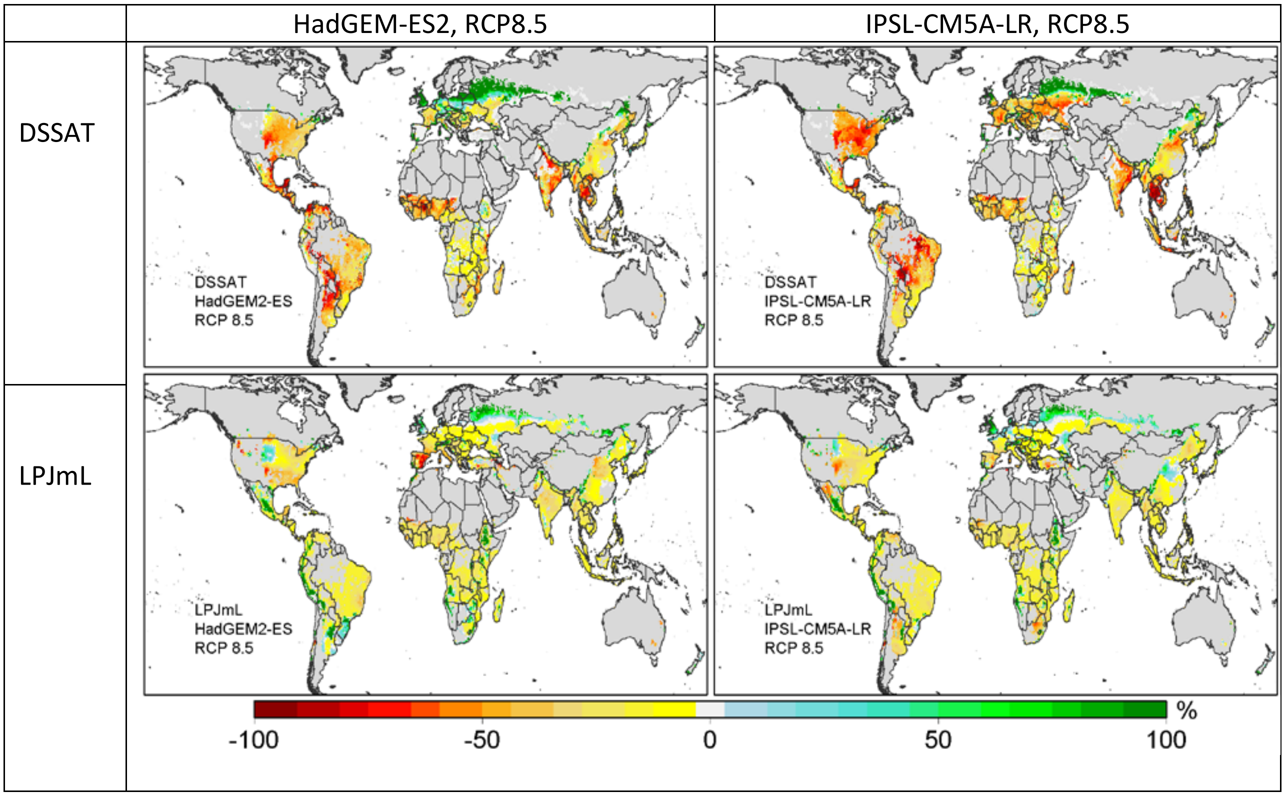
Figure 12. Absolute changes in annual mean temperature [°C] (top) and annual mean precipitation [mm/day] (bottom), 2000-2050



Source: Müller and Robertson (2013).

Figure 13 shows how these temperature and precipitation changes translate into changes in rain fed maize yields as modeled by the DSSAT and LPJmL crop models. The DSSAT modelling results are generally more negative than the LPJmL results but the pattern of changes is roughly the same. The same procedure was followed for all of the crops used in the IMPACT model (see Müller and Robertson (2013) for more details).

Figure 13. Relative changes in rain fed maize productivity climate scenarios for the RCP8.5 emission scenario, 2000-2050



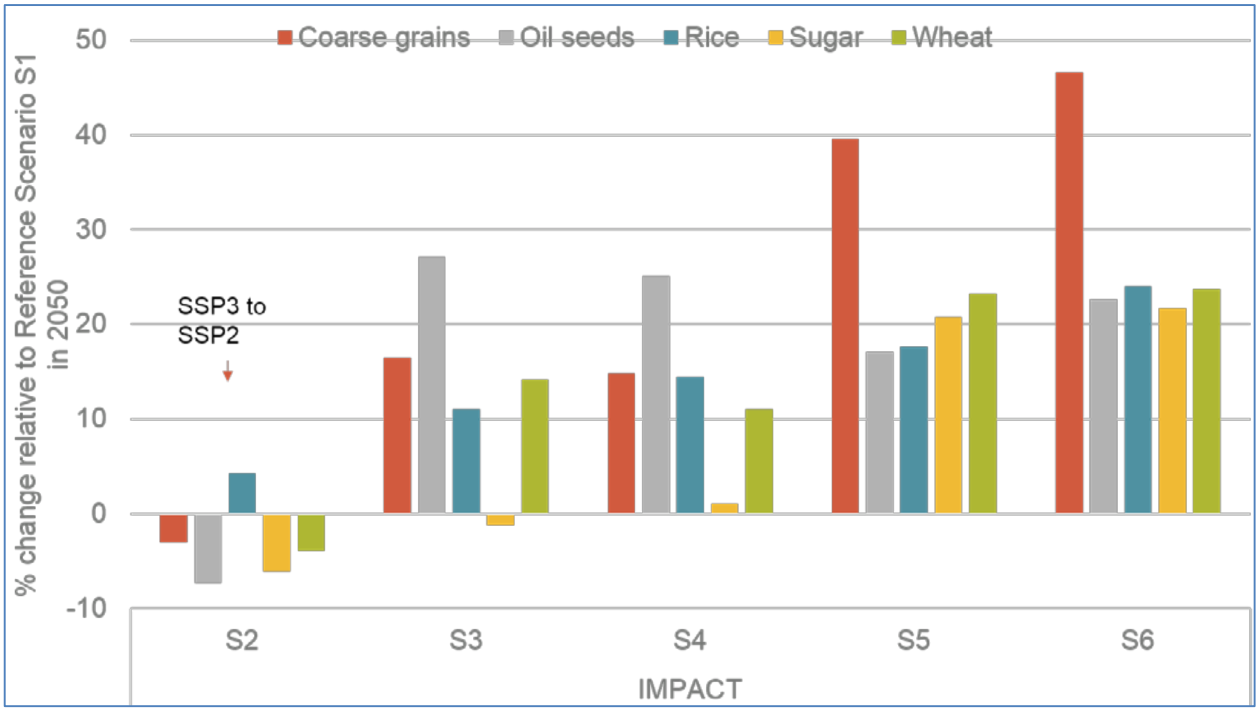
Source: Müller and Robertson (2013).

The consequences of the combined effects or the different socioeconomic and climate drivers are assessed using three metrics – changes in prices, average calorie availability, and the number of malnourished children.

Figure 14 shows the IMPACT-model-based price changes relative to the reference scenario S1, which uses the SSP3 GDP and population growth scenarios and no climate change. In a world with substantially smaller GDP growth and greater population in 2050 (S2 based on the SSP3 drivers) but no climate change, prices of the major commodities shown in Figure 14 decline, with the exception of rice where the lower per capita income in China and India coupled with a higher income elasticity of demand for this starchy staple means greater demand for rice.

For the remaining scenarios that show the effects of climate change on prices in a world with SSP2 drivers, prices are 10 percent to 45 percent higher in 2050 than with no climate change depending on crop and crop model used. The exception is sugar in S3 and S4, where the LPJmL crop model has yield increases from climate change effects (see Müller and Robertson (2013) for more details). Oil seed prices increase the most with the LPJmL results while coarse grains prices increases are greater than other crops with the DSSAT model.

Figure 14. Difference in 2050 prices, comparing socioeconomic effects (S2) and climate change effects (S3 to S6) to S1 (percent)



Source: IMPACT model runs for the AgMIP Global Economic Model Intercomparison Project.

The price increases, driven by income and population growth and climate change, result in changes in production that ultimately affect food availability for consumers. The effects play out in different ways in different countries, depending on how their food systems are affected by climate change, country-specific assumptions about income, population, and agricultural productivity growth and trade flows. Figure 15 and Figure 16 aggregate the country-specific results on average per capita kilocalorie availability to middle-income (Figure 15) and low-income (Figure 16) developing countries.

The two scenarios with no climate change – S1 (using SSP2) and S2 (using SSP3) bracket the range of outcomes. Including the climate change effects with SSP2 shifts the kilocalorie availability in 2050 down, from about 3,400 kilocalories per day to between 3,100 and 3,250 kilocalories per day for middle income developing countries and from about 2,950 kilocalories per day to between 2,700 and 2,800 kilocalories per day for low income developing countries. For middle income developing countries, the climate change effects eliminate most of the benefits from the additional per capita income in the SSP2 scenario. However, for the low-income developing countries, the SSP3 future with no climate change is substantially worse than the SSP2 future with climate change. Of course, an SSP3 future will likely also have significant climate change effects. In the Nelson, et al (2010) results, the pessimistic future with climate change is extremely pessimistic for the low-income developing countries, essentially reducing average kilocalorie availability to near starvation levels.

Figure 15. Daily kilocalorie availability in middle income developing countries

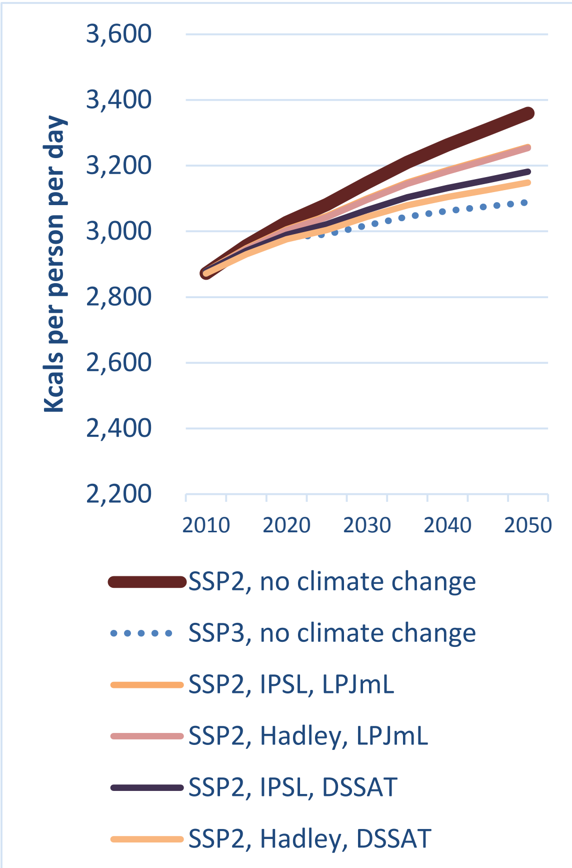
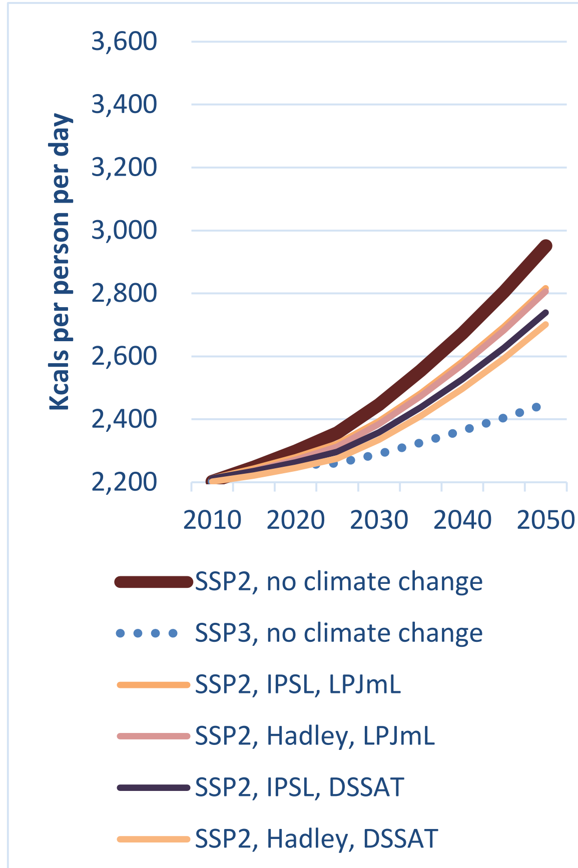


Figure 16. Daily kilocalorie availability in low income developing countries



Source: IMPACT model runs for AgMIP Global Economic Model Intercomparison project

Figure 17 and Figure 18 report the effects of the six AR5-based scenarios for the number of malnourished children in middle- and low-income developing countries respectively. The middle income countries are home to much of the world's population. Hence, although they have the largest numbers of malnourished children, as shown in Figure 17, their relative numbers are smaller. In both country groups, the pessimistic SSP3 future indicated in S2 is the most bleak. In the middle income developing countries, the numbers in S2 fall throughout the period but remain above those for S1, even with climate change. For the low-income developing countries, S2 results in more malnourished children in 2050 than in 2010, even without considering the effects of climate change. By contrast, the strong socioeconomic performance of SSP2 results in substantial declines in the number of malnourished children even while population increases and climate change effects are included. This latter result reiterates the importance of policies and programs that focus on broad-based sustainable economic growth as a powerful driver of improvements in human well-being.

Figure 17. Number of malnourished children in middle income developing countries (million)

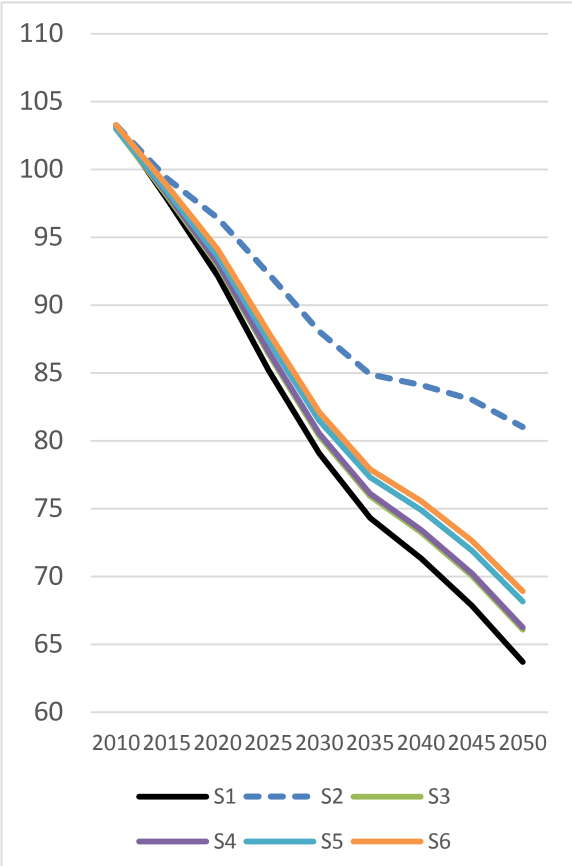
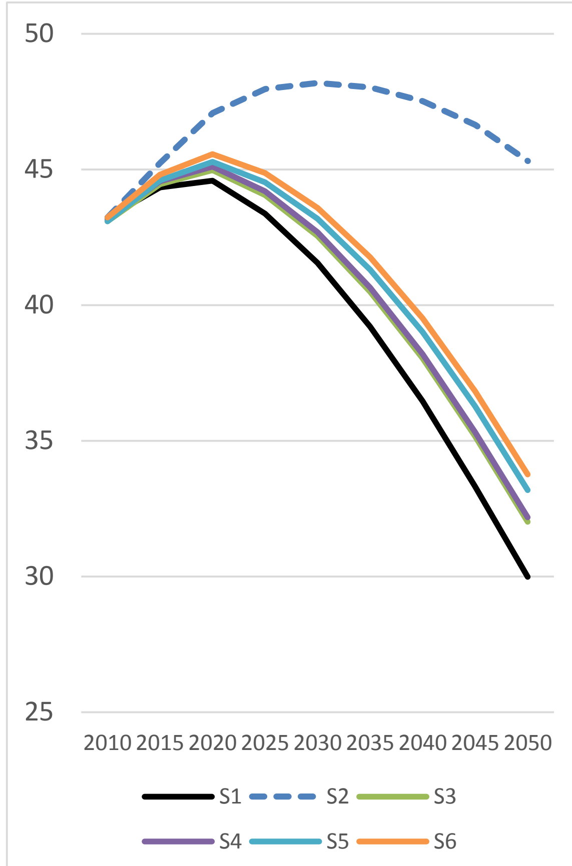


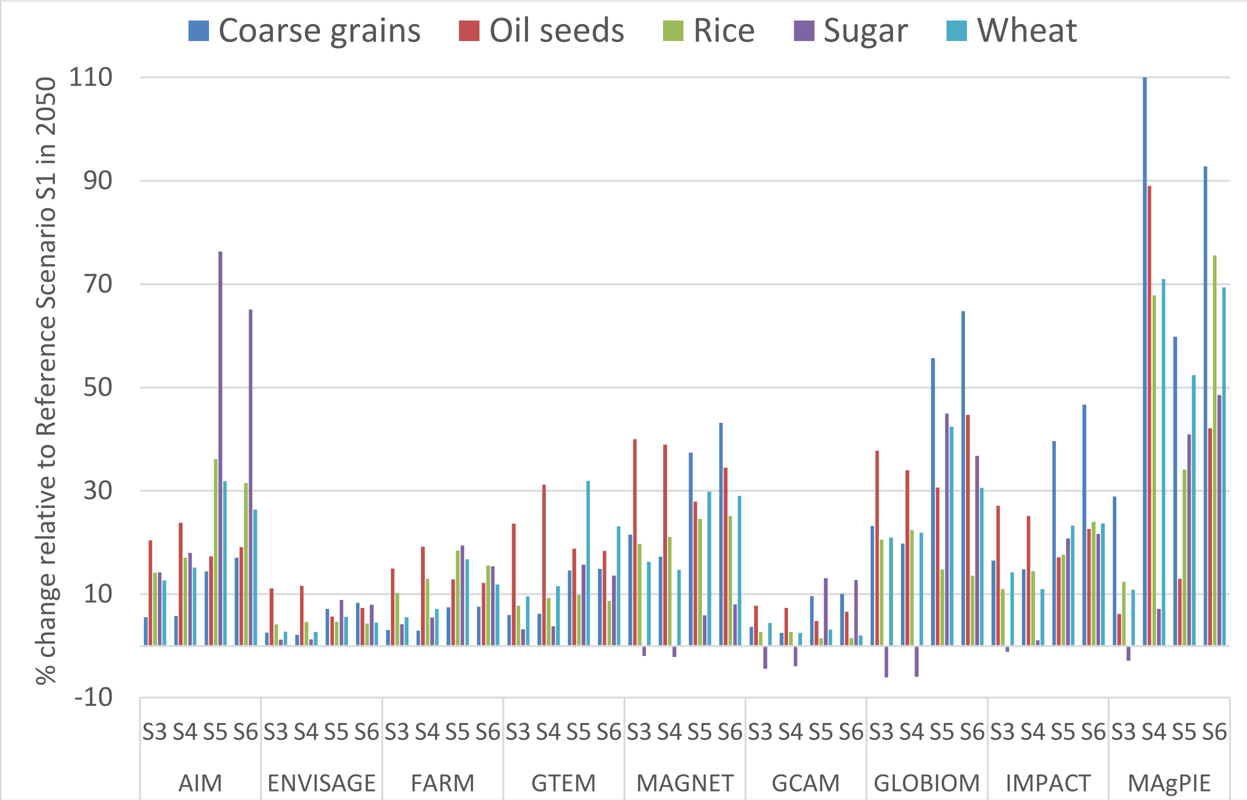
Figure 18. Number of malnourished children in low income developing countries (million)



Source: IMPACT model runs for AgMIP Global Economic Model Intercomparison project

Figure 19 reports price increases in 2050 for the 4 climate change scenarios (S3-S6) for 9 global models participating in the AgMIP global economic model intercomparison effort. To paraphrase an old saying, plausibility is in the eye of the modeler. The IMPACT results displayed above in Figure 14 are reproduced in the second right most set of bars in Figure 19. For all models climate change results in higher prices in 2050, with the exception of sugar in a few models in S3 and S4. But the range of increases is quite large. The FAO/World Bank Envisage model and the GCAM model of the Pacific Northwest National Laboratory report small price increases from climate change, while the MAgPIE model of the Potsdam Institute for Climate Impact Research, the GLOBIOM model of the International Institute for Applied Systems Analysis in Austria and AIM model of the Japanese National Institute for Environmental Studies for S5 and S6 have much larger price increases. The differences reflect varying assumptions about the future of demand for agricultural commodities and the ease with which crop area can be expanded.

Figure 19. Change in 2050 prices, climate change scenarios S3-S6 relative to no climate change (S1) with the SSP2 drivers (percent)



Source: Nelson et al. (2013).

Global trends in agricultural R&D spending

As the results discussed above demonstrate, population growth and climate change will put pressure on our ability to feed the world sustainably. Investments in agricultural productivity are essential to dealing with these challenges. The private sector will invest where it sees opportunities to generate a financial return. Public sector investments are needed to provide the productivity enhancements that are critical but where the nature of the crop (e.g., open-pollinated varieties) or market (consumption of so-called orphan crops by low-income consumers) means the private sector cannot generate an adequate financial return.

We turn now to a brief assessment of recent trends in public and private sector research. This section quotes extensively from the recent publication of the Agricultural Science and Technology Indicators Initiative of IFPRI prepared by Nienka Beintema and colleagues at IFPRI and USDA (Beintema et al. 2012).

Public sector research investment trends

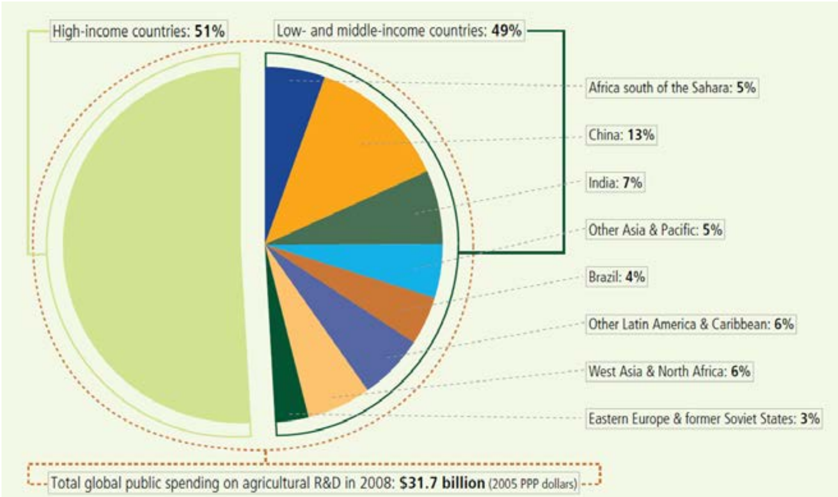
In 2008, global public spending on agricultural R&D totaled $31.7 billion in purchasing power parity (PPP, 2005) dollars. Expenditures were split roughly evenly between high-income countries and low- and middle-income countries, hereafter referred to as “developed” and “developing” countries, respectively (Figure 20). Public agricultural R&D spending in China, India, and Brazil—the three top-ranked countries in terms of public agricultural R&D spending in the developing world—accounted for one-quarter of global spending and half of combined spending in developing countries.

Following a decade of slowing growth at the end of the 20th century, global agricultural R&D spending increased by 22 percent during the 2000–2008 period, from $26.1 to $31.7 billion in 2005 PPP prices (Figure 21). This corresponds to an average growth of 2.4 percent per year, about the same as the 1980s rate (Figure 22). Accelerated R&D spending by China and India accounted for close to half of the global increase of $5.6 billion during 2000–2008.

Interestingly, most of the growth in public agricultural R&D spending in developing countries occurred during the 2005–2008 period and presumably has continued beyond this period as well. In low-income countries, R&D spending grew by 2.1 percent per year during 2000–2008, driven largely by increases in the larger East African countries—Ethiopia, Kenya, Tanzania, and Uganda—after a decade of stagnation in the 1990s and early 2000s. R&D growth for middle-income countries was largely driven by China and India. From 2000 to 2008, spending for middle-income countries grew by an average of 4.4 percent per year (3.2 percent per year when calculations exclude China and India).

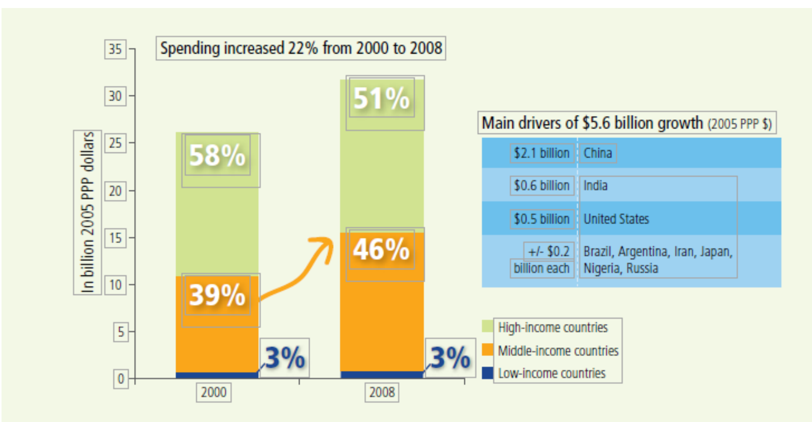
Although recent growth in investments in low- and middle-income countries represent an important turnaround from the previous decades, these increases do not necessarily translate into more research, but to reinvestment in human and physical capital that had decayed after years of neglect; this is particularly the case in Africa south of the Sahara where most of the funds were directed toward much-needed salary increases and the rehabilitation of infrastructure and equipment after years of neglect (Beintema and Stads 2011).

Figure 20. Global public spending on agricultural R&D by major country or region and by income status, 2008.



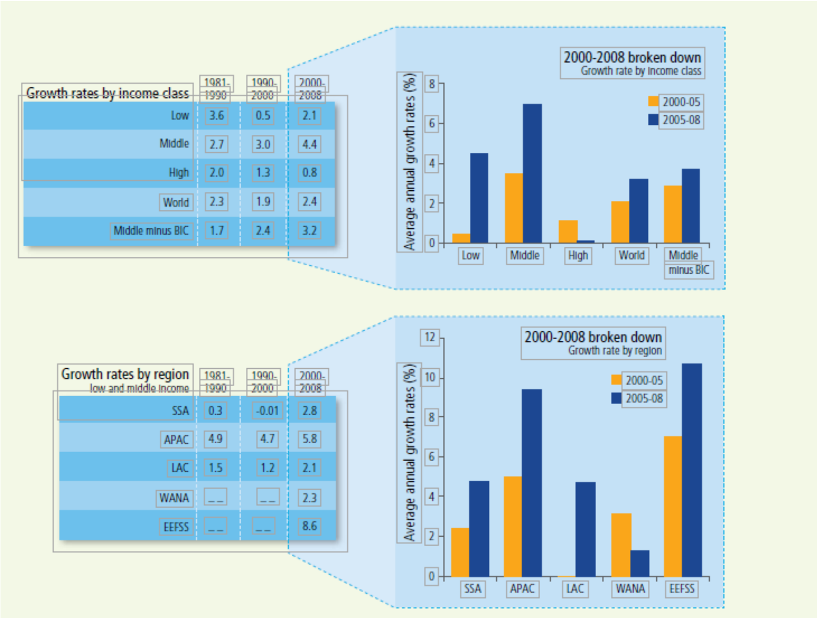
Source of figure: Figure 1 in Beintema et al. (2012). Sources of data: Agricultural Science and Technology Indicators (2012); Eurostat (2012); OECD (2012) and various country level resources.

Figure 21. Drivers of increased spending on global agricultural R&D, 2000–2008



Source: Figure 2 in Beintema et al. (2012).

Figure 22. Average annual agricultural R&D spending growth rates, 1980s, 1990s, and 2000–2008



Source: Figure 3 in Beintema et al. (2012).

High-income countries were an exception to the global growth pattern of the 2000s. In fact, their growth rate in public agricultural R&D investment continued to slow. In the 1980s, spending growth in high-income countries averaged 2 percent per year, but it decelerated thereafter, hovering around zero during 2005–2008. About one-third of the OECD countries spent less on public agricultural R&D in 2008 than they did in 2000. Japan and the United States, with spending levels of $2.7 and $4.8 billion in 2008, respectively, continue to be the top spenders on public agricultural R&D among high-income countries, accounting for half of the OECD total.

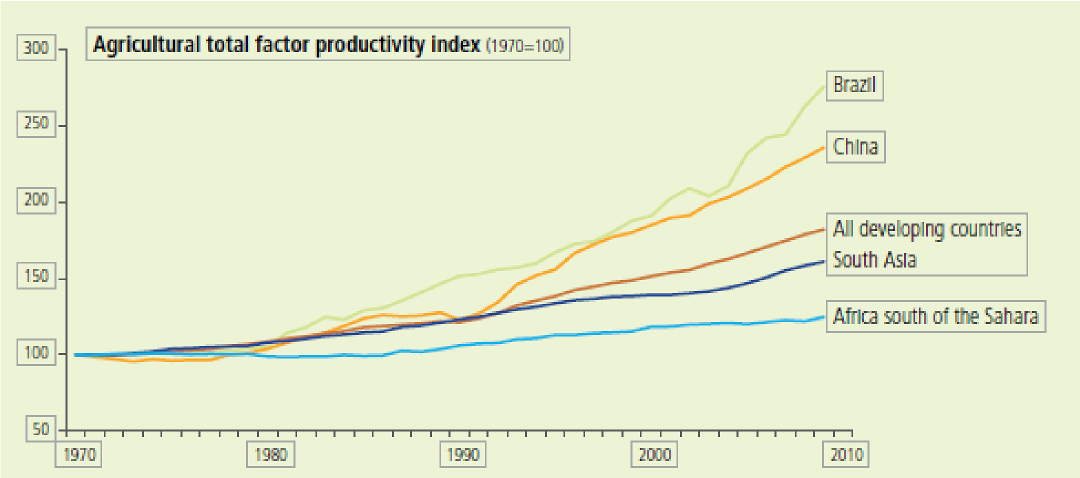
The 31 low-income countries included in ASTI's data synthesis accounted for just 3 percent of total global spending in agricultural R&D. This share remained fairly constant from 1981 to 2008 despite the fact that these countries' share of world population rose from 8 to 10 percent.

International public agricultural research is mostly undertaken by the 15 centers of the CGIAR Consortium. These centers spent more than 700 million PPP dollars in 2011. CGIAR nominal spending increased by 31 percent during 2000–2008 compared a growth of 22 percent for global public spending and increased by an additional 25 percent during 2008–2011 (in inflation-adjusted dollars).

Although the CGIAR plays an important role in agricultural R&D in developing countries, it accounts for only a small share of global public agricultural R&D spending. In 2008, CGIAR spending as a share of total global public agricultural R&D spending amounted to a mere 1.5 percent (3.1 percent, if high-income countries are excluded).

Policy and institutional reforms, as well as a strong commitment to research, lifted agricultural productivity in Brazil and China above the rest of the developing world in the 1980s, and both countries have maintained rapid growth ever since (Figure 23). Besides agricultural R&D, reforms have included improved incentives for farmers, macroeconomic stability, relatively strong extension and rural education systems, and improved rural infrastructure and market access (Chen, Flaherty, and Zhang 2012; Global Harvest Initative 2011). As a result of these policies, both countries experienced sustained higher agricultural growth—measured as total factor productivity (TFP). Between 1970 and 2009, cumulative TFP growth had increased by 176 percent in Brazil and by 136 percent in China compared with 82 percent for developing countries as a whole.

Figure 23. Accelerated agricultural productivity growth in Brazil and China, 1970-2010



Source of Figure: Figure 8 in Beintema et al. (2012). Source of data: Fuglie (2012).

The Indian government has also increased its funding to agricultural research since the late- 1990s but the country has invested a lower percentage of its agricultural output in research than either Brazil or China, both in absolute terms and as a share of its agricultural GDP. Policy and institutional reforms affecting agriculture have also been less pronounced in India than in the other two countries (K. Fuglie and Schimmelpfennig 2010).

Private-sector investment in agricultural R&D

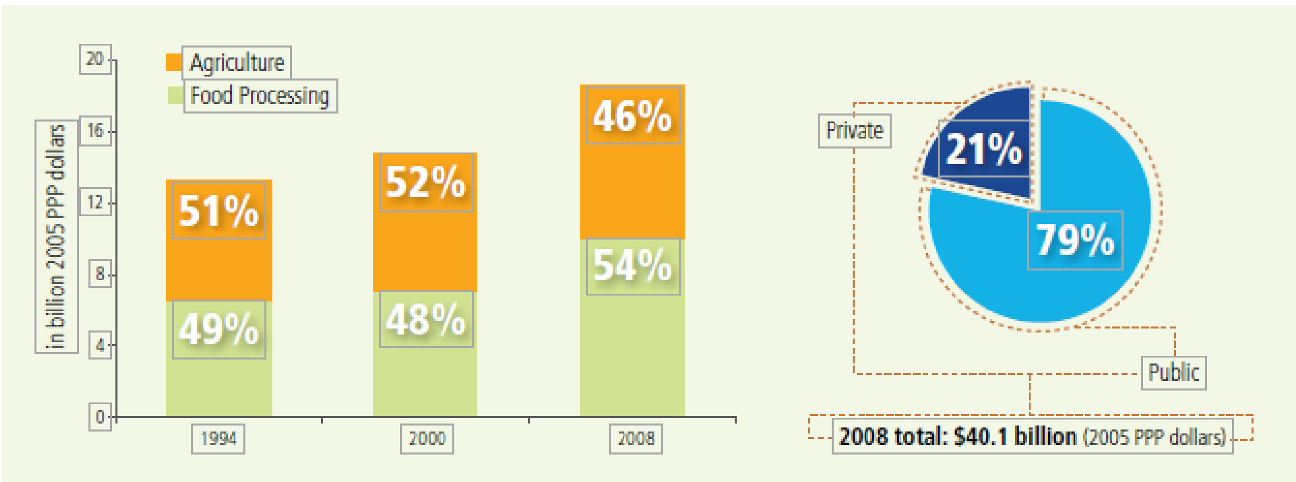
Private investment in agriculture and food processing R&D increased from $12.9 billion in 1994 to $18.2 billion in 2008. About 45 percent of this amount was directed to R&D related to improving inputs used in agricultural production, whereas the remainder was directed to areas related to food processing and product development (Figure 24).

Excluding food processing and product development, global R&D spending by the public and private sectors combined totaled $40.1 billion (PPP) in 2008, of which 79 percent was performed by the public sector and 21 percent by the private sector. Most of the private-sector R&D was carried out by companies based in OECD countries, but many of these companies maintain experiment stations in developing countries in order to transfer new proprietary technologies to these markets (K. O. Fuglie et al. 2011).

Information on private-sector involvement in developing countries remains limited, but evidence suggests significant growth in large middle-income countries. In India, agricultural R&D spending by the private sector has increased five-fold since the mid-1990s (Pray and Nagarajan 2012).

Private companies have also become increasingly active in agricultural R&D in China. In 2006, private-sector spending accounted for 16 percent of total agricultural research spending. As indicated, these figures exclude R&D related to food processing, which also plays an important role in China (Hu et al. 2011).

Figure 24. Global private-sector spending in R&D related to agriculture and food processing



Source of figure: Figure 9 in in Beintema et al. (2012). Original source of data: Fuglie (2012).

The role for public sector agricultural research: productivity increases and human wellbeing

There is consensus that a substantial increase in the quantity of food produced is needed to meet both the population increase expected by 2050 and the growing incomes in the poorer parts of the world. And although we have not been able to satisfactorily model it quantitatively, climate change will bring increased variability in production, which will put added strains on sustainable food security. Productivity increases will be essential. These increases will need to come from some combination of improvements of the plant and animal genetic material used by farmers, both new material and much better dissemination of existing material and the management practices that are need to take best advantage of it. Both types of activities require new resources and in many cases changes in public policy. For some food sources, the private sector will see a financial incentive to invest in the needed productivity and resilience enhancements. But in many parts of the developing world, additional public sector investments, both national and international, will be required. As the discussion in the previous section indicates, public sector investments have been declining until relatively recently and even with the recent turnaround in funding will continue to be scarce. So a key question is to what research activities should this limited set of public sector resources be directed. The priority setting activities currently underway at the FAO and the CGIAR consortium are a critical part of finding the answer to this question.

In this section we provide a very preliminary assessment of the comparative benefits of different types of productivity increases. Since the poorest countries of the world are able to invest the least (as the discussion in the previous section indicates) and are where the bulk of the population growth will take place, we focus on investments in those countries.[6] Using a variety of metrics, we estimate the benefits of increasing yields to 50 percent of the irrigated biological maximum in the currently poorest 39 countries.[7] More precisely, we compute the increase needed in the exogenous yield growth rates in those countries (the IPRs in the IMPACT model) that would generate a yield in 2050 that is half of the value in Table 7, assuming no climate change. Then we run the IMPACT model with the scenarios above and compare the results with and without the improved productivity. We do not have estimates of the costs of developing or disseminating these technologies so we cannot yet estimate which are the most cost-effective.

We examine three metrics – changes in world price, changes in average daily per capita calorie availability, and changes in the number of malnourished children. Because there can be interaction effects (e.g., an increase in maize output reduces maize price which reduces demand for sorghum and lowers the sorghum price) we report both the effects with the single productivity increase and the combined effects for all the crops in Table 7.

Table 7. Assumed maximum biological yield (mt/ha)

Commodity	Maximum potential yield
Cassava	40.00
Chick pea	6.25
Ground nut	8.75
Maize	20.00
Millet	11.25
Pigeon pea	7.50
Potato	65.00
Rice	9.38
Sorghum	16.00
Sweet potato	50.00
Wheat	10.63

Source: Modified from values from those estimated by K. G. Cassman and Justin Van Wart (Univ. Nebraska) for irrigated production.

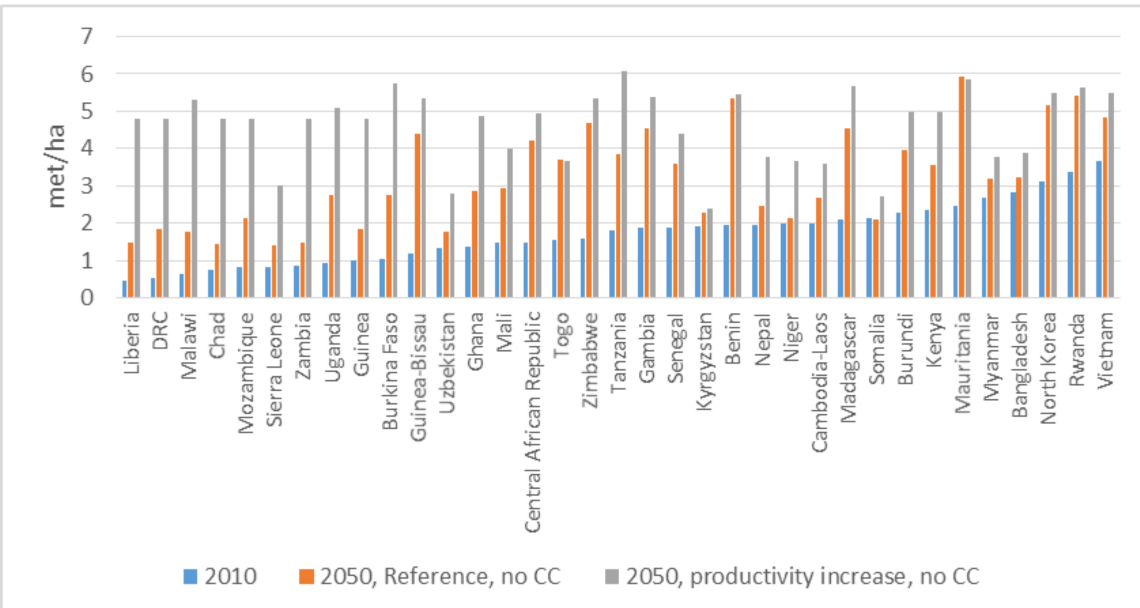
[6] Note that the investments considered in the Nelson et al. (2010) report included developing and developed country productivity increases. Here the focus is just on investments in the lowest income countries.

[7] Afghanistan, Bangladesh, Benin, Burkina Faso, Burundi, Central African Republic, Chad, DRC, Eritrea, Ethiopia, Gambia, Ghana, Guinea-Bissau, Guinea, Kenya, Kyrgyzstan, Liberia, Madagascar, Mali, Mauritania, Malawi, Mozambique, Myanmar, Nepal, Niger, North Korea, Rwanda, Cambodia, Laos, Senegal, Sierra Leone, Somalia, Tajikistan, Tanzania, Togo, Uganda, Uzbekistan, Vietnam, Zambia, Zimbabwe.

Yield effects

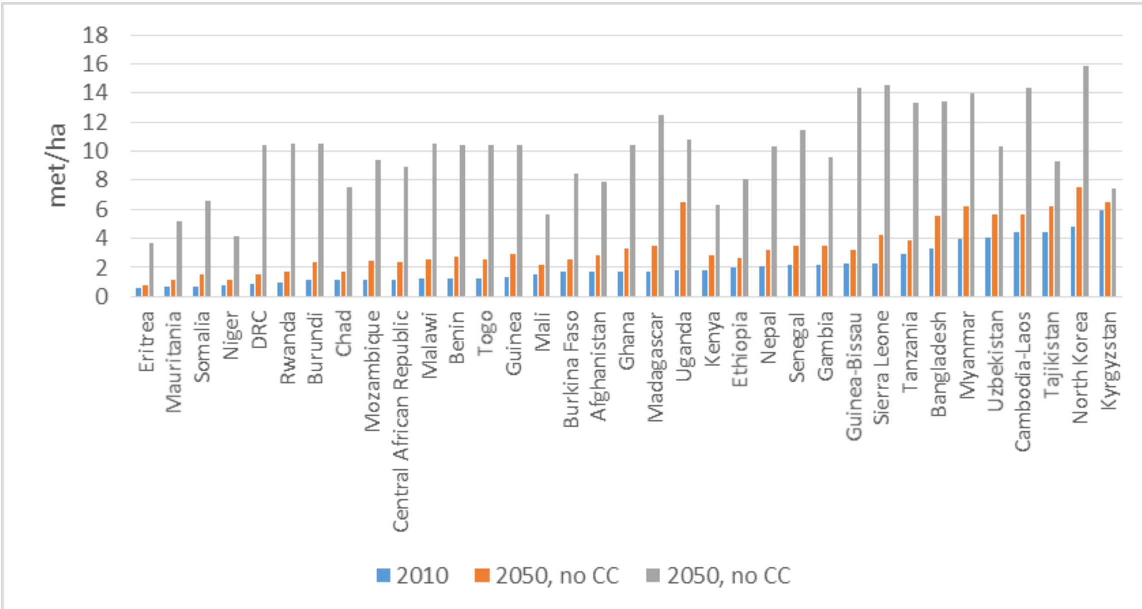
Appendix tables 1, 2, and 3 present detailed yield outcomes for rice, maize, and wheat respectively. Figure 25 to Figure 27 graph these results. For all three crops, the lowest yields today are in countries of Sub Sarahan Africa. For rice, Liberia, DRC and Malawi have the lowest yields; for maize, Eritrea, Mauritania and Somalia; and for wheat, Somalia, Malawi, and Burundi. The results for 2050 without the additional investments roughly parallel those in 2010; that is, if a country had low yields in 2010 it would also be near the bottom in 2050. As expected, with the investments targeted to raise yields to a near a global standard, the differences in 2050 yields are smaller, although they are not identical because of assumptions about national price responsiveness of yields.

Figure 25. National rice yields, 2010 (blue bar), 2050 with no additional investment rice (orange bar), and investment sufficient to raise yield to one half of value in Table 7 (gray bar)



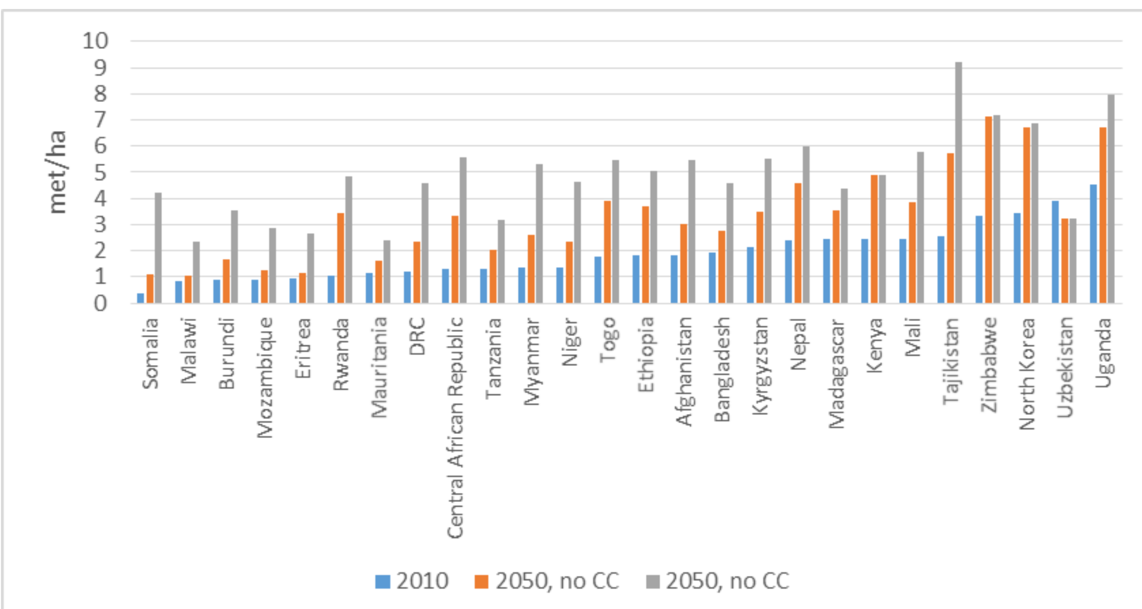
Source: IMPACT model runs for this report.

Figure 26. National maize yields, 2010 (blue bar), 2050 with no additional investment rice (orange bar), and investment sufficient to raise yield to one half of value in Table 7 (gray bar)



Source: IMPACT model runs for this report.

Figure 27. National wheat yields, 2010 (blue bar), 2050 with no additional investment rice (orange bar), and investment sufficient to raise yield to one half of value in Table 7 (gray bar)



Source: IMPACT model runs for this report.

Price effects

Figure 28 to Figure 30 show the effect on prices of the investments as well as the climate change and socioeconomic drivers. In each figure, the left most bar shows the price increases between 2010 and 2050 with no additional investments; the middle bar shows the effects on the price of a crop with an investment only in additional productivity for that crop. The right bar shows the cumulative effect of all investments done simultaneously. The dark blue portion of each bar reflects the changes just from the socioeconomic drivers of SSP2. The light blue portion of each bar is the additional effect coming from negative productivity effects of climate change. The red max/min bars show the range of price differences across the climate change scenarios.

From these figures, we highlight four key findings.

The first point is that the price increases for maize are the largest and rice the smallest. These outcomes combine both supply and demand side factors. SSP2 has strong economic growth that encourages meat consumption which in turn relies on maize for feed. Rice consumption declines with higher incomes in countries where rice is the predominant staple; in addition, Chinese rice production fares relatively well from climate change.

The second point is that the effects from the mean climate change effects and the SSP2 socioeconomic drivers are similar. Climate change is important, but so is broad-based economic growth.

Third, there are dramatic differences in the effects coming from the different climate change scenarios. The results vary by more than the mean of the climate change effects. This finding reinforces the importance of preparing for a wide variety of potential outcomes.

Finally, there are some spillover effects on prices from the various investments. The prices of each of these commodities increases less when all investments are implemented simultaneously than when only one is undertaken. But not surprisingly, the biggest effect on the world price of a crop arises from the productivity investment in that crop.

Figure 28. Rice price change, 2010-2015, various scenarios (percent)

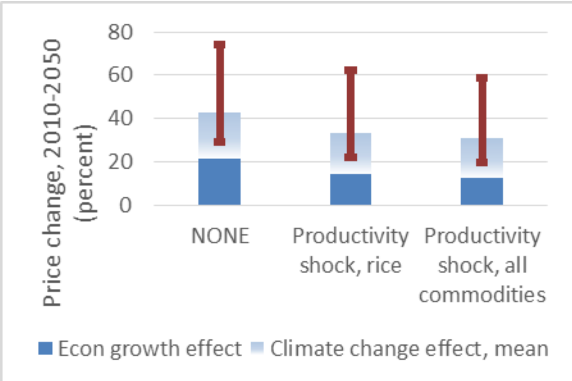


Figure 29. Maize price change, 2010-2015, various scenarios (percent)

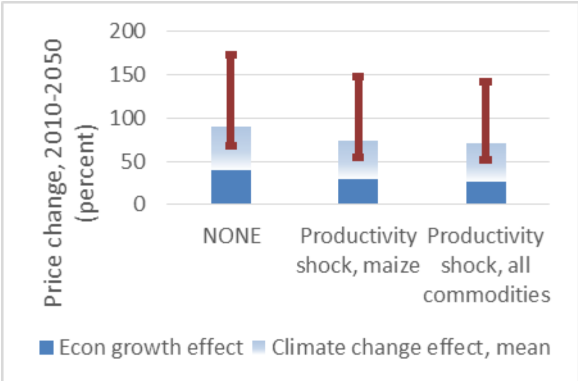
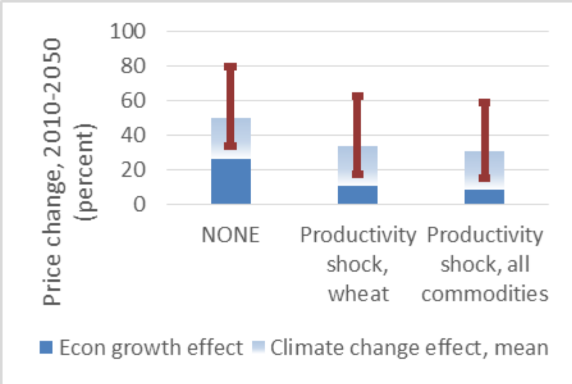


Figure 30. Wheat price change, 2010-2015, various scenarios (percent)



Source: IMPACT model runs for this report.

Calorie availability effects

Economic growth is clearly important to calorie availability as Table 8 indicates; it increases calorie availability by over 40 percent between 2010 and 2050. Climate change is also important in a negative way. The mean effect of climate change is to dampen the benefits from economic growth, subtracting about 8 percent from the growth in calorie availability. But the range of the climate change effects is quite large; from a minimum of 5 to 7 percent decline to a maximum of 11 to 12 percent decline depending on the nature of the productivity increase.

Table 8. Increase in calorie availability, 2010-2050 (percent)

Productivity investment	Economic growth effect	Climate change effect, mean	Econ growth plus climate change mean effect	Climate change effect, minimum	Climate change effect, maximum
None	41	-8	33	-11	-6
Cassava	41	-8	33	-10	-6
Ground nuts	41	-7	34	-10	-5
Maize	42	-9	34	-11	-6
Millet	43	-8	34	-11	-6
Potato	42	-9	33	-11	-7
Rice	42	-8	34	-11	-6
Sorghum	43	-9	35	-11	-6
Wheat	41	-8	33	-11	-6
All	45	-8	37	-11	-6

Source: IMPACT model runs for this report.

Malnourished children effects

Child malnutrition has many determinants, of which calorie intake is one. The number of malnourished children under the age of five is estimated from several variables: the average per capita calorie consumption, female access to secondary education, the quality of maternal and child care, and health and sanitation (Rosegrant et al. 2008). For this report, we assume that life expectancy, maternal education, and clean water access values improve over time but do not change across the scenarios.

Table 9 reports the effects of economic growth (based on the SSP2 drivers) alone on the number of malnourished children, the negative effects of climate change, and the offsetting effects of the various productivity investments. Economic growth reduces the number of malnourished children from 46.3 million in 2010 to 34 million in 2050, a decline of 12.3 million. Climate change offsets some of the benefits of economic growth, adding 2.9 million back for the mean of the four climate change scenarios but with a range of 2.1 million to 3.9 million.

The single-crop productivity investment with the largest beneficial effect is sorghum, reducing the number of malnourished children by 500,000, whether with or without climate change. Millet has the second largest effect on the number of malnourished children, reducing the count by 400,000. These two crops are particularly important food staples in Sub-Saharan African countries, which are disproportionately represented in the group of lowest-income countries. This effect can be more clearly seen by looking at individual country effects. As an illustration of this, Table 10 reports the changes in the number of malnourished children in Mali where millet and rice are important staples. The productivity investments in cassava, maize, potatoes, and wheat have virtually no effect on the number of malnourished children. Millet and rice investments account for the bulk of the decline in malnourished children from an across-the-board investment in productivity increases.

Table 9. Decrease in number of malnourished children in low-income countries, 2010-2050 (million)

Productivity investment	No climate change	climate scenarios		
		mean	min	max
2010	46.3			
2050				
None	34.0	36.9	36.1	37.9
Cassava	33.8	36.7	35.9	37.7
Ground nuts	33.7	36.6	35.8	37.6
Maize	33.8	36.6	35.8	37.7
Millet	33.6	36.5	35.7	37.5
Potato	34.0	36.9	36.1	37.9
Rice	33.8	36.6	35.8	37.6
Sorghum	33.5	36.4	35.6	37.4
Wheat	34.0	36.9	36.1	37.9
All	32.0	34.9	34.1	35.8

Source: IMPACT model runs for this report.

Table 10. Decrease in number of malnourished children in Mali, 2010-2050 (million)

Productivity investment	No climate change	climate scenarios		
		mean	min	max
2010	0.888			
2050				
None	0.677	0.725	0.706	0.748
Cassava	0.680	0.727	0.708	0.751
Ground nuts	0.665	0.714	0.695	0.737
Maize	0.675	0.723	0.704	0.746
Millet	0.663	0.711	0.693	0.734
Potato	0.677	0.724	0.705	0.748
Rice	0.663	0.709	0.690	0.733
Sorghum	0.670	0.718	0.699	0.741
Wheat	0.676	0.724	0.705	0.747
All	0.633	0.681	0.662	0.703

What is missing?

Systematic planning for the future requires an assessment of *all* the key factors that could drive changes. The quantitative modeling community is motivated by providing quantitative assessments of plausible outcomes to assist in this planning but some changes cannot currently be modeled satisfactorily. This information needs to be part of the decision making process as well. Among the issues not well modeled are sources of variability from climate change, under- and over-nutrition, and sustainability.

Climate change

There are two phenomena of particular importance related to climate change that have not yet been satisfactorily captured in the scenario work described here. The most important is the increased weather variability that is likely to occur with climate change. Satisfactory modeling of its effects requires models that can incorporate variability explicitly and none of the global economic models currently do this. But even if they could the climate modeling community is not able to generate estimates of the change in variability for the weather variables of most importance for agriculture.

The second area is in the crop model response to pest pressure. Climate change is likely to increase the incidence and nature of threats from various agricultural pests. But the crop models don't have many satisfactory methods of implementing changes in pest pressure. But even if they did, there are virtually no quantitative assessment of how climate change will affect the incidence of even the most common pests. These two lacunae deserve particular attention from the research community.

Malnutrition

Only a few of the global models report estimates of average daily per capita kilocalorie availability (see for example the results from the AT 2012 report displayed in Figure 9 and the IMPACT model results in Figure 15 and Figure 16 and Table 8) and the basis for these numbers is somewhat shaky. There is little or no scenario work available that looks at changes in calorie consumption for different groups and nothing available on other nutrients. And overnutrition is a growing problem in today's developing countries and the quantitative global modeling work has virtually nothing to contribute to the discussion.

Sustainability

Although virtually everyone agrees that sustainable food security is very important there is little agreement on which of the many potential dimensions of sustainability are most important to assess. Currently available global models can already assess some dimensions of sustainability – land use change, use of water, nutrient use, greenhouse gas emissions – but there has been no systematic effort to review these metrics, how the models implement them, and what key aspects of sustainability are missing.

Priorities for the CGIAR and FAO in scenario development and strategic foresight

Both the CGIAR and FAO are currently undertaking enhancements to their scenarios modeling. As indicated above FAO is moving from a system that relies almost exclusively on expert opinion to a more quantitative modeling approach, with an emphasis on general equilibrium modeling. IFPRI is the CGIAR center that undertakes most of the CGIAR-based global modeling and is currently enhancing its system to incorporate more detailed biophysical modeling and is working with some of the world's leading crop modelers to better model explicitly potential biophysical productivity improvements as part of its Global Futures project.

It is clear that substantial resources are needed to sustain the detail of modeling and model improvements that are needed. This suggests that cooperation across these two sets of institutions to take advantage of their expertise could result in better understanding for all. At the same time, neither of these institutions has some of the expertise badly needed to assess the coming food security challenges so cooperation should extend to a range of research organizations. We envision three types of joint activities.

Cooperative quantitative modeling

The FAO's ENVISAGE model is one of the world's leading global computable general equilibrium (CGE) models with detailed (from a CGE perspective) representation of agriculture. The feature of CGE models that is of particular importance is that they can explicitly deal both with the effects of agricultural investments and policy changes on other parts of the economy and with the effects of changes outside of agriculture on that sector. IFPRI's IMPACT suite of models, which includes a partial equilibrium, multi-market model with high spatial and product resolution, and soft links to a detailed hydrology model, a water supply-demand model, and the DSSAT suite of crop models, is one of the world's leading partial equilibrium model with highly developed links to biophysical modeling. Soft linking of these two modeling environments would allow better representation of plausible outcomes of potential public sector research activities, as well as a range of other potentially important public and private sector activities. Other CGIAR centers have expertise in certain kinds of biophysical models (e.g., ruminants at ILRI and agroforestry at ICRAF) as does FAO (e.g. aquastat). An effort to identify best-of-breed data and tools at these two institutions, integrate as appropriate, and share them as open source public goods would undoubtedly have high returns.

At the same time, other research centers have developed critical tools such as process-based crop modeling software that are essential to priority setting. Partnerships with these institutions will be essential to make most productive use of the resources devoted to CGIAR and FAO activities.

Cooperative use of institutional and outside substantive expertise

One of the strengths of the AT process at FAO is its extensive consultation with subject matter expertise at FAO. The IMPACT suite has also had ad-hoc consultation with experts in the CGIAR centers. But scenario/foresight work at both institutions would benefit from a regular, systematic review process by internal and external subject matter experts of the inputs (e.g., biological potential in response to management and climate changes) and outputs (e.g., location-specific yields, planting and harvest dates, production levels).

Sustained cooperation with model intercomparison efforts

While both the IMPACT suite and ENVISAGE represent state of the art models for scenario/strategic foresight, there are several other global models produced by advanced research institutes that have dimensions not captured by these two models and internal expertise that results in model outcomes that can differ substantially, as the price ranges in Figure 19 demonstrate. The AgMIP project (www.agmip.org) has intercomparison and improvement of agricultural models of all kinds as its *raison d'être*. Cooperation by FAO and the CGIAR with these other modeling efforts under the auspices of AgMIP will improve all the models involved in the comparison.

A role model to consider is the Stanford-based Energy Modeling Forum (EMF) that has been active since the energy crises of the 1970s. EMF currently convenes the best energy modelers from around the world to focus on specific issues related to energy and (since the 1990s) greenhouse gas emissions. The simple fact that membership, which is voluntary and non-remunerated, is so high is an indication of the value of the network for the researchers who participate and/or the agencies for which they work. Agriculture, like energy, is facing huge challenges over the next decades, with or without climate change. The ability to pool the best analysts from around the world will enhance the individual efforts of the research terms as well as provide policy makers—national and international—with improved analysis, which, not necessarily reflecting consensus, reflects more considered and insightful analysis.

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Appendix

Appendix table 1. Rice country-specific yield outcomes, without and with additional exogenous productivity growth

		Reference results				Rice productivity increase results			
			Climate scenarios				Climate scenarios		
	2010	2050, no CC	Mean	Min	Max	2050, no CC	Mean	Min	Max
Bangladesh	2.84	3.23	3.54	2.96	3.95	3.88	4.34	3.54	4.97
Benin	1.94	5.33	3.62	2.85	4.30	5.46	3.75	3.00	4.41
Burkina Faso	1.06	2.77	1.88	1.53	2.18	5.74	4.04	3.45	4.46
Burundi	2.30	3.96	3.43	3.01	3.87	4.98	4.31	3.81	4.86
Central African Republic	1.50	4.21	3.76	3.25	4.27	4.93	4.40	3.82	4.98
Chad	0.76	1.45	1.13	1.04	1.17	4.79	3.88	3.73	4.28
DRC	0.53	1.85	1.85	1.56	2.15	4.78	4.80	4.06	5.60
Gambia	1.89	4.53	3.74	3.17	4.31	5.37	4.47	3.72	5.22
Ghana	1.38	2.86	2.10	1.97	2.30	4.86	3.60	3.29	4.02
Guinea-Bissau	1.20	4.39	4.33	3.32	5.27	5.35	5.34	4.04	6.55
Guinea	1.02	1.85	1.43	1.30	1.62	4.78	3.74	3.22	4.50
Kenya	2.36	3.57	3.14	2.83	3.45	4.97	4.37	3.96	4.79
Kyrgyzstan	1.91	2.29	2.49	2.36	2.64	2.38	2.59	2.44	2.76
Liberia	0.46	1.50	1.11	0.66	1.55	4.80	3.54	2.12	4.94
Madagascar	2.11	4.53	4.35	3.77	5.00	5.67	5.44	4.71	6.26
Mali	1.48	2.93	1.89	1.33	2.42	4.00	2.55	1.79	3.29
Mauritania	2.48	5.94	4.33	3.35	5.29	5.87	4.28	3.31	5.23
Malawi	0.65	1.78	1.64	1.44	1.82	5.29	4.92	4.28	5.53
Mozambique	0.81	2.13	2.01	1.80	2.24	4.81	4.59	4.09	5.12
Myanmar	2.70	3.18	3.64	2.71	4.69	3.79	4.44	3.13	5.96
Nepal	1.95	2.48	2.58	2.27	2.83	3.76	3.98	3.27	4.60
Niger	1.99	2.14	1.58	0.88	2.72	3.67	2.61	1.37	4.48
North Korea	3.13	5.16	6.00	5.47	6.57	5.48	6.25	5.70	6.86
Rwanda	3.37	5.41	4.99	4.12	5.81	5.63	5.24	4.32	6.13
Cambodia-Laos	2.01	2.67	2.75	2.26	3.21	3.59	3.93	3.06	4.86
Senegal	1.90	3.61	3.12	3.07	3.27	4.38	3.81	3.71	3.98
Sierra Leone	0.81	1.42	1.39	1.29	1.48	3.00	2.74	2.34	3.13
Somalia	2.15	2.11	2.23	1.84	2.85	2.73	2.86	2.34	3.67
Tanzania	1.81	3.85	3.62	3.13	4.16	6.09	5.81	4.99	6.77
Togo	1.56	3.70	3.28	3.04	3.62	3.67	3.24	3.02	3.57
Uganda	0.95	2.75	2.55	2.15	2.91	5.09	4.84	4.00	5.67
Uzbekistan	1.33	1.78	1.52	1.15	1.73	2.79	2.31	1.63	2.70
Vietnam	3.68	4.82	4.14	4.02	4.30	5.49	4.68	4.52	4.89
Zambia	0.86	1.49	1.27	1.17	1.37	4.81	4.11	3.79	4.45
Zimbabwe	1.58	4.68	4.82	4.73	4.91	5.33	5.49	5.38	5.59

Appendix table 2. Maize country-specific yield outcomes, without and with additional exogenous productivity growth

			Reference results			Rice productivity increase results			
			Climate scenarios				Climate scenarios		
	2010	2050, no CC	Mean	Min	Max	2050, no CC	Mean	Min	Max
Afghanistan	1.72	2.87	2.47	2.21	2.63	7.92	7.18	6.68	7.56
Bangladesh	3.28	5.57	5.15	4.92	5.40	13.45	11.90	11.06	12.80
Benin	1.22	2.72	1.80	1.33	2.18	10.40	6.94	5.16	8.38
Burkina Faso	1.68	2.60	2.16	1.46	2.64	8.45	6.70	4.35	8.27
Burundi	1.12	2.33	2.11	2.02	2.20	10.50	9.80	9.27	10.23
Central African Republic	1.18	2.36	2.04	1.96	2.12	8.89	7.61	7.29	7.91
Chad	1.12	1.74	1.43	1.21	1.83	7.53	6.16	4.98	8.11
DRC	0.83	1.55	1.41	1.33	1.48	10.40	9.49	8.99	9.96
Eritrea	0.60	0.74	0.70	0.69	0.71	3.64	3.35	2.89	4.03
Ethiopia	2.04	2.62	3.11	2.78	3.37	8.13	9.81	8.67	10.68
Gambia	2.23	3.50	2.82	2.43	3.15	9.55	7.80	6.78	8.70
Ghana	1.74	3.33	2.21	1.51	2.71	10.40	6.97	4.81	8.51
Guinea-Bissau	2.25	3.18	2.84	2.60	3.21	14.40	12.85	11.79	14.53
Guinea	1.31	2.90	2.14	1.82	2.31	10.40	7.72	6.62	8.31
Kenya	1.83	2.83	2.96	2.78	3.16	6.34	6.59	6.26	6.98
Kyrgyzstan	5.90	6.52	6.95	6.02	7.48	7.42	8.00	6.73	8.75
Madagascar	1.74	3.45	3.01	2.47	3.53	12.47	10.93	9.02	12.76
Mali	1.51	2.19	1.82	1.54	2.03	5.67	4.49	3.66	5.26
Mauritania	0.64	1.14	1.21	1.03	1.49	5.21	5.36	4.26	6.92
Malawi	1.21	2.54	2.38	2.37	2.39	10.50	9.84	9.78	9.89
Mozambique	1.17	2.49	2.14	1.95	2.34	9.40	8.10	7.39	8.85
Myanmar	3.99	6.18	4.94	4.16	5.64	13.95	11.42	10.37	12.40
Nepal	2.13	3.17	2.64	2.48	2.84	10.37	8.72	8.33	9.26
Niger	0.81	1.16	1.08	1.02	1.20	4.14	3.72	3.27	4.41
North Korea	4.78	7.48	6.79	5.71	7.75	15.82	14.40	12.22	16.36
Rwanda	0.92	1.76	2.06	1.76	2.36	10.50	12.25	10.53	13.95
Cambodia-Laos	4.39	5.68	3.70	2.35	4.72	14.36	9.42	6.05	11.97
Senegal	2.18	3.50	3.12	2.71	3.31	11.48	10.38	9.08	10.91
Sierra Leone	2.27	4.25	3.40	3.20	3.76	14.51	11.58	10.89	12.82
Somalia	0.66	1.50	1.26	1.08	1.44	6.59	5.91	5.00	6.86
Tajikistan	4.47	6.25	5.23	4.48	6.16	9.27	7.65	6.44	9.13
Tanzania	2.91	3.85	3.68	3.60	3.77	13.30	12.66	12.38	12.92
Togo	1.26	2.59	1.81	1.44	2.07	10.40	7.34	5.88	8.36
Uganda	1.82	6.49	6.57	5.51	7.75	10.79	10.88	9.25	12.69
Uzbekistan	4.06	5.69	4.36	3.72	5.15	10.31	7.66	6.41	9.22

Appendix table 3. Wheat country-specific yield outcomes, without and with additional exogenous productivity growth

				No shock				Maize shock	
			Climate scenarios				Climate scenarios		
	2010	2050, no CC	Mean	Min	Max	2050, no CC	Mean	Min	Max
Afghanistan	1.85	3.03	3.28	2.93	3.93	5.49	6.15	5.39	7.52
Bangladesh	1.93	2.76	2.14	2.07	2.29	4.59	3.51	3.22	3.80
Burundi	0.88	1.65	1.44	0.93	1.70	3.54	3.02	1.82	3.62
Central African Republic	1.29	3.31	2.90	2.62	3.24	5.55	4.78	4.26	5.40
DRC	1.21	2.34	2.06	1.98	2.10	4.58	3.97	3.81	4.04
Eritrea	0.93	1.15	1.10	1.04	1.14	2.65	2.57	2.00	3.03
Ethiopia	1.80	3.71	3.13	2.82	3.25	5.03	4.22	3.79	4.40
Kenya	2.45	4.91	4.81	3.97	5.55	4.89	4.80	3.96	5.53
Kyrgyzstan	2.13	3.48	3.26	2.80	3.62	5.54	5.18	4.45	5.74
Madagascar	2.43	3.56	2.95	2.87	3.04	4.35	3.56	3.45	3.67
Mali	2.46	3.84	3.41	3.26	3.70	5.77	5.08	4.77	5.51
Mauritania	1.14	1.64	1.32	1.08	1.64	2.40	1.84	1.40	2.42
Malawi	0.82	1.07	1.00	0.93	1.06	2.36	2.09	1.83	2.26
Mozambique	0.90	1.25	1.13	1.07	1.16	2.86	2.45	2.29	2.57
Myanmar	1.34	2.61	2.06	1.75	2.29	5.32	4.20	3.60	4.66
Nepal	2.41	4.60	3.78	3.22	4.17	5.98	4.92	4.21	5.42
Niger	1.38	2.34	1.95	1.15	2.96	4.61	3.44	2.27	4.86
North Korea	3.43	6.74	7.35	6.23	8.90	6.85	7.48	6.35	9.06
Rwanda	1.06	3.44	3.22	2.96	3.41	4.86	4.55	4.17	4.82
Somalia	0.38	1.10	0.77	0.58	0.99	4.21	3.13	2.15	4.37
Tajikistan	2.54	5.74	5.22	4.88	5.61	9.24	8.42	7.88	9.04
Tanzania	1.31	2.03	2.01	1.89	2.15	3.19	3.07	2.85	3.33
Togo	1.79	3.92	3.15	2.89	3.40	5.48	4.42	4.06	4.75
Uganda	4.55	6.74	6.32	5.68	6.73	7.99	7.62	6.72	8.23
Uzbekistan	3.92	3.23	3.43	2.13	5.54	3.23	3.43	2.13	5.54
Zimbabwe	3.31	7.14	6.01	4.69	6.83	7.18	6.04	4.71	6.87