INVESTMENT REQUIREMENTS UNDER NEW DEMANDS ON WORLD AGRICULTURE:

FEEDING THE WORLD WITH BIOENERGY AND CLIMATE CHANGE

Siwa Msangi, Simla Tokgoz, Miroslav Batka and Mark Rosegrant*

SUMMARY:

In this paper, we explore the sectoral spending that is needed to sustain global agricultural food production at the level needed to feed the world to 2050. We examine the key sectors most closely associated with agricultural performance and human well-being improvement, and see how these sectoral needs change under the additional challenge of the future climate change. The results of our analysis reveal a significant level of additional spending needed for key regions like sub-Saharan Africa and South Asia, which hold most of the world's poor and undernourished, and which will be hard-hit by climate change. The role of irrigation becomes important for regions like Africa, which heavily depend on rainfed agricultural production. The need for roads is also crucial as a means for increasing the market access of producers and maintaining a vigorous level of performance within agriculture and other sectors. We discuss the role of the international agricultural research system in terms of providing global public goods, in the form of research innovations that benefit the global food system through both higher levels of availability, under increasing environmental and socio-economic stress, and through lower food prices.

ACKNOWLEDGEMENTS:

The authors gratefully acknowledge the invaluable assistance of Leonard Gwanmesia, in the writing and revisions of this paper, and for the comments and assistance of Nienke Beintema and staff of the ASTI project.

1. INTRODUCTION

The role and significance of key global drivers of agricultural supply and demand have been at the forefront of the policy debate that has emerged over the last two years, given the dynamics of food and energy prices that have been observed in global and national markets (Evans, 2008; FAO, 2008). The underlying factors to these rapid increases in food prices are varied – both in nature and in their relative strength in driving the market dynamics across various commodities. Among the large number of factors that have been attributed to the volatile state of food prices, are the rapid increase in first-generation, food-based production of biofuels (Oxfam International, 2008; Runge and Senauer, 2008), as well as the increase of cereal and meat and dairy demand from East and South Asia, and the possibility of increased speculative trading and purchasing activity in food markets. Several comprehensive discussions of this issue have appeared in recent literature, and try to assess the relative merit of each of these factors – while also including an overview of the global macro-economic picture, and the relative decline of the dollar, in relation to other currencies (Abbot et al., 2008). The steady decline in the global level of cereal stocks as a result of various factors including the private sector taking over the operation of cereals stocks from government (Trostle, 2008), has also been cited as a factor that has reduced the ability of national governments to stabilize consumer and producer prices (OECD, 2008). Most authors, however, do not isolate a single cause as being to blame for the current world food situation, but cite a complex interaction between several coincident factors.

* Paper written in support of the FAO Expert Meeting on "How to Feed the World in 2050." The views expressed in this information product are those of the author(s) and do not necessarily reflect the views of the Food and Agriculture Organization of the United Nations.

Contact: Siwa Msangi, Senior Research Fellow, Environmental Production and Technology Division
International Food Policy Research Institute (IFPRI)
2033 K Street, NW, Washington, DC 20006
Email: s.msangi@cgiar.org

The challenges and increased stresses that face global food production and distribution systems, in the present economic climate, are particularly acute and pressing for sub-Saharan Africa, where roughly thirty-three percent of the population of sub-Saharan Africa lives with insufficient food supplies (FAO, 2005) and an even greater proportion, forty-three percent, lives below the international dollar poverty line (Dixon et al., 2001). The constraints that lie in the way of Africa benefiting from higher producer prices of agricultural commodities on the world market are myriad, and include the fact that most of Sub-Saharan Africa's agricultural production relies on rainfed cultivation, and receives lower input levels of improved seed technology and fertilizer applications relative to other regions.

In this paper, we look at the resources and investment needs for agriculture for sustaining the required growth in food production through the medium- and long-term periods, and the additional challenges that climate change and other environmental stresses are likely to present. We discuss the necessity for widely-available agricultural research benefits and innovations, and look at the role of the international agricultural research system from the perspective of providing global public goods. Next, we examine the baseline case of growth to 2050, in order to understand the relative size and distribution of investment needed in both the key agricultural and non-agricultural sectors most closely associated with food security and human well-being, and then examine the additional needs that climate change will likely require. Based on this analysis, we conclude with some final recommendations for both policy action and interventions, as well as for further research and analysis.

2. INVESTMENTS TOWARDS AGRICULTURE

2.1 Agricultural R&D relative to other drivers of change

There are a number of underlining factors that drive the long-term trends in global food supply and demand that have also contributed towards a tightening of global markets in the past decade. These trends are driven by both environmental and socio-economic changes, as well as by agricultural and energy policy, including those which govern investments of public and private entities towards agricultural research and development. Figure 1 illustrates the interactions between the various key 'drivers' of change in global food systems, and their linkage to other components of the food economy and to important outcomes of human well-being – such as nutrition (Figure 1).

While this schematic is not completely exhaustive of all the major factors of importance, it incorporates the main elements of global environmental and economic change in food production and consumption systems, that we hope to address in this paper. While Figure 1 does show how the various drivers of change interact with each other, and where the critical feedback loops might be – it does not provide us with the type of distinguishing characteristics that can explain short-lived and long-lived effects on food systems. Figure 2, however, does more to make this distinction, and shows where some key drivers of change lie in relationship to each other, with respect to their dynamic characteristics – which is a combination of the speed with which they act, as well as the degree to which they explain short-term or long-term phenomena (Figure 2).

Aside from the drivers of socio-economic change, in the form of increasing growth in population numbers and total income, which constitute the major factors that govern the change in demand for food and energy products over time, there are a number of key supply-side drivers which must be taken into account. A number of key environmental factors might restrain the supply side of food systems from responding readily and consistently to changes in demand – as a result of either resource scarcity or degraded land and water quality. Reduced research investments in crop and energy technology could also lead to a longer-term slowdown in the expansion of supply – which eventually leads to higher prices, as demand continues to grow. This is the particular aspect of the global food problem that we address in this paper, to better understand how the current and past trends in agricultural research investments can result in a less resilient agricultural system and a more food-insecure future, given the challenges that the climate change and the bioenergy present to the global food economy.

A number of future assessments of global food production and consumption show projections of future agricultural land requirement that assume that 70 percent of food needs will be met through yield enhancements

(FAO, 2006). Yet, agricultural research has stagnated or declined over the years for many regions particularly after the 1990's (Table 1). For developing countries, public agricultural research investments increased by 37.4 percent between 1991 and 1981, where this growth rate declined to 21.8 percent between 2000 and 1991. For developed countries, this decline is even sharper; the growth rate declined from 28.7 percent to 5.9 percent for the same time frame. For sub-Saharan Africa, which is particularly vulnerable to food security problems, public research investments actually declined. Given the vast number of studies that show the existence of significant R&D spillovers, a decline or stagnation of research in any of these regions may have adverse impacts agricultural productivity in other regions as well. Table 1 also presents the agricultural research expenditures as a percentage of agricultural GDP. It can be seen that this share has declined for sub-Saharan Africa over the years, whereas it increased only slightly in the other regions (Table 1).

As the United States of America and other developed regions have shifted their research focus to reflect consumer preferences for processed, organic, and humane products, the diffusion of more relevant yield enhancing technology in developing countries has slowed (Pardey *et al.,* 2006). Only one-third of the global public agricultural research in the 1990s was in developing countries, with over 50 percent being concentrated in Brazil, China, India, and South Africa (Pardey *et al.,* 2006). Therefore, better technology diffusion and more public funds dedicated to developing country research programs are critical to meet the growing food needs.

2.2 Agricultural productivity and the 'public goods' problem

Global agricultural production has a multifaceted and widely-varied landscape that encompasses a wide range of farming systems and agro-ecologies. The distribution of crop species has been governed by a gradual diffusion of technology and knowledge that has evolved over decades and centuries of innovation, knowledge-sharing, dissemination, commercial interaction, and natural dispersion by environmentally-driven forces of change. As a result of this, there are a number of characteristics of the wider agricultural technology portfolio that are public as well as private in nature. On-farm technologies and capital can be considered as fully privatized and within the control of the individual (or household) that has acquired it through purchase or gradual acquisition and accumulation over time. Aside from individual know-how, intelligence, ingenuity and gifted-ability, a great deal of agricultural knowledge can also be accumulated or purchased from the market, in the form of hired expertise or education. Agricultural extension constitutes a publicly-provided good which has limits to scope and coverage, at the country-level, and might not be sufficient in quantity and quality to benefit all those who need it. The global pool of agricultural technology and knowledge that consists of various plant genetic resources, improved seed varieties that have varied abilities within different agro-ecologies and environmental regimes, can be thought of as the knowledge that is embodied in the international agricultural research centers (IARCs) and global bodies such as the Food and Agricultural Organization (FAO) of the United Nations and other regionally- and internationally-sponsored (and funded) bodies.

While many would agree on the utility and benefits provided by the system of international research bodies and affiliated organizations, in terms of strengthening the performance and resilience of agriculture both at a regional and global scale, the question of how to finance such a system of centers remains open to debate – as it is not in the interests of any one organization or government to donate resources towards an entity whose benefits will diffuse well beyond the scope of its constituents or borders. Aside from the questions of accountability and governance, the long-term goals and objectives of such agricultural research organizations extend beyond the usual time horizon that national politicians would care to consider, when they contemplate the opinions of the constituents who elect them, and the short-term actions that are needed to influence them. Therefore, there remains a mismatch in objectives and incentives when we consider the motives that underlie the decision to make investments or contributions towards agricultural research and crop productivity improvement.

The voluntary contributions problem

We use a simple example to illustrate the problem of individual agencies (or countries) making voluntary contributions towards agricultural research, when the benefits of those contributions cannot be fully appropriated or captured by them, and extend beyond the scope of their constituents' interests. This 'voluntary contributions' problem[1] contains the key elements of a non-cooperative strategic equilibrium, and is a well-understood case from the public economics literature, which demonstrates the properties of a sub-optimal, Nash equilibrium outcome. In other words, we obtain a final outcome that results in lower overall welfare than that which would happen if a more altruistic and all-encompassing outlook were used to decide on the optimal level of investment to place in public research to enhance global agricultural productivity.

To illustrate this problem, we take a simple case in which we hypothesize a national entity (or a representative agent who acts on behalf of the national good) and who derives 'utility' (benefit) from the consumption of both food and non-food goods (c_f, c_{nf}) within the country. The consumption of these goods, however, must be balanced with the contribution (x) that must be made towards a global public good (agricultural productivity research) that enables the production of the food good to be sustained and made available (through trade or food aid, *f.ex.*) at the global level. As the national entity must make this contribution (along with *N-1* other nations), and do so at the expense of the national budget, then there is a trade-off that arises in the mind of the national decision-maker between the national utility of consuming both the food and non-food goods, and the contribution that must be made (at the expense of non-food consumption) towards the global public good, which is generated through voluntary contributions.

Following the logic of Laffont (1988), we represent the national entity's utility as being separable between the consumption of the non-food good which is financed from the national 'treasure' and of the food good (which is enabled by the global public good), such that

$$\begin{aligned}
& u^i\left(c_{nf}^i - x^i, c_f^i\right) \\
& \textit{where} \\
& c_{nf}^i + x^i \leq Y^i \quad \textit{and} \quad c_f^i = g_f\left(x^i + \sum_{-i} x^{-i}\right)
\end{aligned}$$

Where the creation of the global public good depends on the contribution of each national agency *i* and all other nations (*-i*), and where the national income is Y^i. In the case where this utility is being maximized at the country-level, we can assume that choices will be made such that the national budget is spent (and the constraint is binding), so that we can represent non-food consumption as ($Y^i - x^i$), and we can substitute the equation that relates food consumption to the public good, such that expression for national utility becomes

$$u^i\left(Y^i - x^i, c_{nf}^i\right) = u^i\left(Y^i - x^i, g_f\left(x^i + \sum_{-i} x^{-i}\right)\right) = u_1^i\left(Y^i - x^i\right) + u_2^i\left(g_f\left(x^i + \sum_{-i} x^{-i}\right)\right)$$

assuming that a separability exists between the food and the non-food consumption, in the national utility function. Using simple logarithmic functions, we can translate our conceptual framework into the following maximization problem

$$\max_{x^i} \quad \alpha \log\left(Y^i - x^i\right) + \beta \log\left(g_f\left(x^i + \sum_{-i} x^{-i}\right)\right)$$

---

[1] For further details on these kind of public economics problems, see Laffont (1988).

where the individual level of contribution towards the global public good (x^i), is the only decision variable for the national agency. We obtain the following necessary condition, for the maximization of the national agent's utility[2]

$$\frac{-\alpha}{Y^i - x^i} + \frac{\beta}{g_f\left(x^i + \sum_{-i} x^{-i}\right)} g_f{}'\left(x^i + \sum_{-i} x^{-i}\right) = 0 \quad \rightarrow \quad \frac{\alpha}{Y^i - x^i} = \beta \cdot \frac{g_f{}'\left(x^i + \sum_{-i} x^{-i}\right)}{g_f\left(x^i + \sum_{-i} x^{-i}\right)}$$

If we impose the symmetry condition, of a Nash equilibrium, in which each agent conjectures that the actions of all the other *N-1* players will be identical to their own, then we can re-write the maximization condition after substituting $\tilde{x}^i = \tilde{x}^{-i} = \overline{x}$, to obtain

$$\frac{\alpha}{Y - \overline{x}} = \beta \cdot \frac{g_f'\left(N \cdot \overline{x}\right)}{g_f\left(N \cdot \overline{x}\right)}$$

if we take the function g_f $g_f\left(\square\right)$ to be a simple linear function ($g_f\left(x\right) = k \cdot x$), then we would obtain the following relationship

$$\frac{\alpha}{Y - \overline{x}} = \beta \cdot \frac{g_f'\left(N \cdot \overline{x}\right)}{g_f\left(N \cdot \overline{x}\right)} = \beta \cdot \frac{k}{k \cdot N \cdot \overline{x}} = \frac{\beta \cdot}{N \cdot \overline{x}} \quad \rightarrow \quad Y - \overline{x} = \frac{\alpha N}{\beta} \cdot \overline{x}$$

which results in a Nash equilibrium, in which the optimal decision of each national agent is given by

$$\overline{x} = \frac{Y}{1 + \frac{\alpha N}{\beta}}$$

From this result, we can see that as the number of agents increases – the level of voluntary contributions from each individual decreases, monotonically (i.e. $\overline{x} \rightarrow 0 \; as \; N \rightarrow \infty$).

This result can be contrasted with that of the 'global social planner' who considers the welfare of all *N* nations, and solves the problem, below

$$\max_{x} \quad N \cdot \left[\alpha \log\left(Y - x\right) + \beta \log\left(g_f\left(\sum_{i=1}^{N} x^i \right) \right) \right]$$

which results in the solution $\hat{x} = \dfrac{Y}{1 + \dfrac{\alpha}{\beta}} > \overline{x} = \dfrac{Y}{1 + \dfrac{\alpha N}{\beta}}$, and a higher level of contributions to the global public good, than under the Nash equilibrium outcome.

In reality, the problem of providing for a global good through a contributory scheme can also have elements of foresight (versus myopia) involved, whereby the long-term benefits might be overlooked by an agency that is much more short-sighted in terms of their policy horizon – which are usually bounded by the span of periodic election cycles for national politicians. We will not address the issue of myopia analytically, here, but appeal to

---

[2] which is obtained by taking the derivative with respect to *x*

the reader's intuitive expectation that a far-seeing global agency would do better at providing for a public good than a short-sighted national agency would.

3. GLOBAL OUTLOOKS FOR AGRICULTURE AND INVESTMENT

In this section, we present some empirical examples to illustrate the importance of investments in agriculture, and the implications that sub-optimal policies can have for future food production and human well-being, if attention is not paid by policy makers. Before delving into the particulars of the investment scenarios that are illustrated, we take some time to explain the methodological approach used in calculating the future investment needs in agriculture.

3.1 Methodology used for quantifying necessary agricultural spending

The types of investment and sectoral spending that are tracked within the IFPRI modeling framework are spread over 3 key areas:

(1) Direct investment in agricultural research and development spending
(2) Investment in key sectors that are strongly linked to agricultural productivity growth – roads and irrigation
(3) Expansion of non-agricultural services and sectors that have been shown to have highly positive impacts on human well-being improvement – especially the reduction of malnutrition and hunger. Chief among these areas of spending are those of education (especially female secondary schooling), the provision of clean drinking water (and accompanying improvements in sanitation) and expansion of healthcare services that result in significant improvements in human life expectancy.

These areas of spending represent the sectors that have, empirically, the most significant impact upon the human well-being measure of malnutrition in the highly vulnerable demographic of pre-school children which are tracked in the simulations of the IFPRI agricultural policy model (IMPACT) (Rosegrant *et al.*, 2001). The linkages created between these sectors and the model outputs are shown in the schematic, in Figure 3, and illustrate the areas in which various drivers of socio-economic growth, policy and environment can interact with elements of the food system to lead to different outcomes of nutrition and human well-being (Figure 3).

In trying to account for how the influence of agricultural spending leads to improvements in agricultural performance and, subsequently, to nutrition and well-being, we face a number of key challenges. The first of these challenges is to account for the lagged effects that expenditures on agricultural research have on productivity and performance of agricultural production systems. This is a topic that has been researched within a variety of settings – particularly that of the United States of America, where the data on agricultural research spending and regional-level agricultural production and yields are available over a long period (enabling detailed econometrics to be carried out). Such work has been carried out by key authors such as Alston *et al.* (1998, 2002) and Marra *et al.* (2002). The volume of work that has been carried out to document the impact of agricultural research spending in the developing work is far smaller, due to the data problems that are often encountered when attempting to obtain a long enough time series over which to carry out empirical estimation and measurement. A few key examples that we have drawn upon are those of Alene and Coulibaly (2009), who looked in detail at the Africa region. Another key data gap that we face in carrying out our own quantification is the level of agricultural research spending that has taken place in the Central Asian countries. The comprehensive database of Agricultural Science and Technology Indicators (ASTI) that is maintained by IFPRI, provides us with invaluable information, that has enabled us to plug many of the data gaps that would otherwise be insurmountable (ASTI 2009).

In terms of a final methodological note, we should point out that our approach to quantifying the investment needs in agriculture and other related sectors does not attempt to optimize across the various options, in order to come up with a least-cost solution to increasing agricultural sector performance. In many ways, this would be an appealing approach to take, and would be in the spirit of a normative analysis that attempts to guide investment decisions in the best possible manner, so as to maximize social welfare and gains. However, the definition of the objective function would be complicated – as it would most likely need to satisfy a number of goals and criteria, and not just a single objective. The weighting among these various goals that would result in the single scalar valued objective function value would also have to be subject to scrutiny and sensitivity analysis. While this remains an appealing direction of analysis, we defer it for now to further research, and adopt an approach which 'searches' in a less efficient manner over the space of interventions, for that which results in a "no-impact" solution with regard to a pre-defined outcome. In other words, we show how changes in the levels of spending in these sectors can offset the human costs of decreased agricultural performance and productivity, as measured through increases in the levels of child malnutrition, so that we can quantify the size of the interventions that might be necessary to offset shocks to food economies, such as those brought on by environmental shocks or policy-changes.

3.2 Baseline projections of spending needed for agriculture

In this section, we present some projections of spending on agriculture that are anticipated under a baseline set of assumptions, regarding the growth of crop yields and productivity in agriculture. We will contrast the baseline case with one in which there is an effort to offset the effects of climate change – as envisioned under one of the more severe climate scenarios – in order to illustrate the levels of spending and improvement that are needed to address the challenges that global environmental change will pose to the global food system.

By looking at the baseline case to 2050, projected with IFPRI's IMPACT model, we see that the implied spending across both the agricultural and non-agricultural sectors implies sizable outlays of resources, in order to meet the future needs for food, feed and fuel (Table 2).

From this table, we see that a sizable outlay of expenditure is still needed in South Asia to maintain its irrigation system, in order to continue the successes and the momentum of the green revolution. This is reflected in the strong increases in irrigated area that are projected to continue in South Asia, compared to what is seen in other regions (Figure 4).

Even though there are increases in irrigated area in sub-Saharan Africa, they are modest in size, compared to other regions – which reflects that historical difficulty in realizing successful irrigation investments there, and the notoriously high costs of those which are implemented (IWMI, 2005). For the rest of Asia and the Pacific, clean water investments remain the largest category for which future spending needs lie. There is also a higher share of regional spending that is allocated to rural road access, compared to South Asia. The region that has the highest share of its expenditure allocated to rural road access is sub-Saharan Africa followed closely by Latin America and the Caribbean (Table 3).

The largest amount of spending that is envisioned for agricultural research is in Latin America and the Caribbean as seen in Table 2,which is necessary to change the pattern of historical production growth which has mostly come from land expansion, into a future pattern of growth that relies more on yield increases. The future changes in regional environmental conditions across Latin America, in future, will also require it to adapt its agricultural sector, accordingly.

For the sub-Saharan Africa region, a more even spread of the investment outlays is envisioned across all components of the agricultural sector. The largest category of spending for sub-Saharan Africa, across all sectors, is that of improving access to clean water. Given that access to clean drinking water is such an important part of household health and welfare, and the fact that it has been slow to spread to those parts of rural sub-Saharan Africa that need it most, it remains a 'big ticket' item on Africa's spending bill. Irrigation investments is the second largest component to counteract the historically very low rate of irrigation expansion and adoption across the continent, South Asia also has a large outlay of expenditure for improving access to clean water, given the large number of the poor and the malnourished in that region. Figure 5, below, shows the change in the levels of access to clean water across various regions, which are used as exogenous assumptions in the IMPACT simulations.

Spending on female secondary education is also a large portion of the non-agricultural spending portfolio for both Asia and sub-Saharan Africa, given that it has also accounted for a large share of the reduction in child malnutrition seen in the past years, and because the rapidly growing populations of these regions are projected to have sizable increases in the population of school-age girls in the coming years (Table 2). Figure 6 shows the rates of female secondary school enrollment that are embedded into our baseline simulations, and which imply increasing numbers of girls that are educated over time.

Therefore in order to maintain, and continue to improve the enrollment rates of females in secondary school, the pace of future expenditure has to increase into the future in order to accommodate these new pupils.

3.3 Addressing the challenge of climate change in agriculture

Now we examine the case where we introduce a climate change scenario, into our modeling framework, and simulate the projected shocks to agricultural production and the future patterns of food consumption, availability, and malnutrition that result from that. We then carry out a policy experiment, in which we introduce yield improvements to the affected crops and regions, and determine the additional levels of agricultural sector spending, above the baseline case, that are necessary to offset the shocks introduced by climate change. The results provide us with insight into which countries are most affected by the climate change shocks, and where the additional spending on agriculture is needed more. The results of this scenario analysis will provide policy makers and agricultural researchers and scientists with a sense of prioritization of their efforts in coming years.

For this experiment, we take a more ‘extreme’ climate change scenario, generated by the Hadley Center’s climate change model. The IPCC’s “A2a” scenario provides us with such a case, where we have rather sharp decreases in precipitation for South Asia, as well as key parts of sub-Saharan Africa and Latin America. Table 4 shows us the additional expenditure within the agricultural sector that we see as necessary to bringing the world food system back to the “no climate change” case.

From this table, we see that sub-Saharan Africa requires the largest level of spending in agriculture, in order to offset the impacts of climate change, as measured within this modeling framework. Within that total spending level for Africa, the amounts for irrigation and agricultural R&D are close in magnitude. The level of investment needed in rural roads is more than quadruple of the amount of investments needed in all the other sectors combined. Given the poor state of road networks in Africa, and the large share of the population that is projected to remain rural in the future (implying higher road costs necessary to reach them), the levels of spending in this category are relatively large, compared to other regions, and constitute a significant increase over the baseline spending needs for roads. The next largest level of outlay in roads is Latin America, given its relatively low population density, compared to Asia, which also raises the costs of reaching people by road.

The additional spending on agricultural research is highest in sub-Saharan Africa among all regions, followed by Latin America and the Caribbean region and the Middle East and the North Africa region. These additional spending requirements show the need to maintain the increases in yield growth (over area expansion) that are required in order to produce the high volume of cereals needed for food and feed, as environmental and socio-economic changes occur to 2050.

4. IMPLICATIONS FOR FOOD SECURITY AND POLICY

In light of these impacts, and given the nature of the policy problem that we have previously described, within the context of the various global and regional drivers of change, we might consider several possible entry points for policy intervention, which might address the global food situation and the challenges that will be faced to 2050. As is shown in Figure 1, there are a number of interventions which we could consider that will impact the supply side response to continuing demand growth. The first is to boost the output of cereals by raising yield levels over time through policies that accelerate the improvement of crop technologies. This can be done directly through improved seed technologies, which might enhance the productivity and hardiness of plant varieties, or through the expansion of area under irrigated production, which has a higher yield than the rainfed alternatives, typically. Improved seed technologies can even reduce the loss in productivity that occurs when irrigated crops become water-logged or subject to increased salinity and submergence – thus allowing the expansion of irrigated area to be even more effective in raising the overall production levels.

This suggests that a combination of policy interventions are necessary when dealing with the world food situation – in the same way that a complex combination of factors were originally responsible for its evolution towards the present state. The maintenance or acceleration of yield growth over time is another part of the policy combination that should also be pursued, as it will have a profound effect upon the trajectory that future food system dynamics will follow. There is also a long lag-period between the time that such investments are made, and the time higher growth potential is realized. Part of this call is now being taken up by the global development donor community, and will be followed up by increased commitments towards R&D spending from both the public and the private sources. It must, however, be accompanied by concurrent improvements in extension services and improvements in marketing and distribution infrastructure, which can only come from national governments and from concrete allocations in public spending, in order to be realized at the farmer/field-level. Regional development agendas, such as the Comprehensive African Agricultural Development Program (CAADP), are trying to lead regional policy bodies and national governments through the necessary steps of making these commitments towards agriculture-focused public spending increases – and require the analytical support of researchers and policy analysts to better refine their targets and define the appropriate domains for intervention.

Furthermore, due to the existence of significant R&D spillovers between countries and regions, investments in agricultural research in one country will also benefit other countries. Thus, for every dollar spent on R&D activities in a country, the resulting gains will be shared by multiple countries and regions. This further illustrates the importance of continuing R&D activities and generating knowledge that will help farmers increase their production and meet growing domestic and international demand.

In the case of climate change, a country experiencing sharp decreases in crop productivity due to more variable or adverse climatic conditions, can decide to decrease the area under cultivation of that crop within the country, and to meet its domestic demand through imports. On the other hand, the same country might decide to switch towards a more resilient crop variety, that is more tolerant of extremes in either temperature or rainfall conditions. However, this requires mechanisms that go beyond just trade movements, and needs a robust and productive system of agricultural research to make these improved varieties available. The improved varieties that come through the system of international agricultural research centers could provide these as global public goods, and supplement the efforts of those regions which still lack the capacity to produce them locally. This suggests a vital role for climate focused agricultural research for the future decades.

5. LIMITATIONS AND SCOPE FOR FURTHER WORK

In this paper, we have tried to quantify the additional requirements needed to maintain the necessary trajectory of growth and human well-being in face of the additional stresses posed to the food system through crop-based bioenergy growth and climate change. The particular sectors that we addressed our analysis to, however, are not exhaustive of the entire range of spending that will likely be needed to upgrade and reinforce the facets of the food system that will be most vulnerable to the pressures of these global drivers. In this analysis, we have not taken into account the expected replacement costs of on-farm capital, and how these might be accelerated with the affects of climate change – as little evidence exists to indicate what these costs would be. There are not additional food storage, distribution and processing capacity investments that are included in this analysis, nor are there any investments in improved information or early warning systems that could provide additional knowledge and decisions support to farm operators and managers to better adapt and adjust to emerging pressures and further improve the efficiency of the sector. The numbers that are given in this paper represent the additional level of spending that are critical to strengthening the particular linkages to human well-being that are described in figure 3. There is further work that we will do to refine the methodology of accounting for information resource needs, and other types of infrastructure that might not have been addressed here. There are also some aspects of adaptation that we have not been able to fully address, within the context of climate change. The ability of certain regions to improve efficiency, substitute labor-intensive for capital-intensive methods and upgrade material and equipment to increase yield and energy intensity has not been modeled explicitly, and will also be addressed in future work once better information is available. We, nonetheless, take our analysis as being strongly indicative of the key sectors that will warrant further attention and support in the coming decades.

6. CONCLUSIONS

In this paper, we illustrate the investment needs that are required to enable agricultural production and the wider food system to meet the challenges of feeding the world to 2050, under increased environmental and socio-economic stresses. Development and long-term economic growth will inevitably lead to more capital- and energy-intensive patterns of production over time. Within this context, it remains the role of technological efficiency improvements – in both industry and agriculture – to relieve the pressures that this growth will place on the natural resource base and on the landscape. This underscores the need for continued investment in yield-enhancing crop technologies that can lessen the reliance on crop area expansion to increase food production, that can improve the resilience of agriculture to climatic change and variability, as well as in technologies that can allow biofuel production to switch away from food-based feedstocks, towards those which can use non-staple and even non-edible plants or plant material. Having higher commodity prices might raise the returns that make investments in these areas more attractive, and, in the case of biofuels, for example, there might be the need for some support in first-generation biofuel sectors, in order to allow the second-generation to emerge more quickly. However, policymakers need to strike a careful balance between providing necessary incentives while also offering the protection that is needed for those who are most vulnerable.

This requires a more concentrated effort on the part of researchers and policy analysts to help identify where such opportunities might exist, and where the returns to investment might be the highest. Meeting the world's growing needs for food, feed, and fuel will inevitably put greater pressure on production systems, and on the natural resources and ecosystems that support them. Therefore, balancing the needs of agricultural development and economic growth, with the goal of achieving long-term environmental sustainability and a diverse set of important goals for human well-being improvement, will require a concerted effort to coordinate development policy objectives, mobilize needed resources and deploy the necessary technologies and interventions where they are most effective and needed.

REFERENCES

ASTI (Agricultural Science and Technology Indicators). 2009. ASTI Online. Available at http://www.asti.cgiar.org/

Alene, A.D. and O. Coulibaly. 2009. The Impact of agricultural research on productivity and poverty in sub-Saharan Africa. *Food Policy*, 34: 198-209.

Alston, J. M., Craig, B. J. and Pardey, P. G. 1998. "Dynamics in the creation and depreciation of knowledge, and the returns to research:," EPTD discussion papers 35, International Food Policy Research Institute (IFPRI).

Alston, J.M., M.C. Marra, P.G. Pardey, and T.J. Wyatt. 2000. A Meta Analysis of Rates of Return to Agricultural R&D: Ex Pede Herculem? Washington D.C.: IFPRI Research Report No 113.

Cline, W. 2007. Global Warming and Agriculture: Impact Estimates by Country. Center for Global Development. Washington DC, USA.

Dixon, J., A. Gulliver, and D. Gibbon. 2001. *Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World.* Washington D.C. and Rome: Food and Agriculture Organization and World Bank.

Evans, A. 2008. Rising Food Prices: Drivers and Implications for Development. Briefing Paper 08/02, Chatham House, United Kingdom.

FAO (Food and Agricultural Organization of the United Nations). 2008. Soaring Food Prices: Facts, Perspectives, Impacts and Actions Required. Paper prepared for the High-level Conference on World Food Security "The Challenges of Climate change and Bioenergy". HLC/08/INF/1. FAO,Rome.

FAO. 2006. World agriculture: towards 2015/30. Rome: Food and Agricultural Organization of the United Nations.

FAO. 2005. Background Paper for 31st Session of the Committee on World Food Security "Impact of Climate Change, Pest and Disease on Food Security and Poverty Reduction," May 23-26.

IWMI. 2005. Inocencio, A., Kikuchi, M., Tonosaki, M., Maruyama, A., and H.

Sally. 2005. Costs of irrigation projects: a comparison of sub-Saharan Africa and other developing regions and finding options to reduce costs. Pretoria: IWMI. (Report of component study for Collaborative Programme).

Laffont, J.J. 1988. Fundamentals of Public Economics. MIT Press.

Marra, M. C. & Pardey, P.G. and Alston, J.M. 2002. "The payoffs to agricultural biotechnology: an assessment of the evidence," EPTD discussion papers 87, International Food Policy Research Institute (IFPRI), Washington DC.

OECD (Organization for Economic Cooperation and Development). 2008. Rising Food Prices: Causes and Consequences. OECD, Paris.

OECD-FAO (Organization for Economic Cooperation and Development and Food and Agricultural Organization of the United Nations). 2008. Agricultural Outlook 2008-2017. OECD, Paris.

Oxfam International. 2008. Another Inconvenient Truth: How Biofuels Policies are Deepening Poverty and Accelerating Climate Change. Briefing Paper 114, Oxfam International.

Pardey, P.G., J.M. Alston, and R.R. Piggott, eds. 2006. Agricultural R&D in the developing world: Too little, too late? Washington DC: International Food Policy Research Institute.

Rosegrant, M. W., M. S. Paisner, S. Meijer, and J. Witcover. 2001. *Global food projections to 2020: Emerging trends and alternative futures*. Washington, D.C. International Food Policy Research Institute.

Rosegrant, M.W., X. Cai, and S. Cline. 2002. *World water and food to 2025: Dealing with Scarcity*. Washington, D.C. International Food Policy Research Institute.

Rosegrant, M.W., S. A. Cline, W. Li, T.B. Sulser, and R. Valmonte-Santos. 2005. *Looking Ahead: Long-Term Prospects for Africa's Agricultural Development and Food Security*. 2020 Discussion Paper No. 41. Washington, D.C.: International Food Policy Research Institute.

Runge, C.F. and B. Senauer. 2008. How Ethanol Fuels the Food Crisis, Author update May 28th 2008, *Foreign Affairs*. http://www.foreignaffairs.org/20080528faupdate87376/c-ford-runge-benjamin-senauer/how-ethanol-fuels-the-food-crisis.html

Schmidhuber, J. 2006. 'Impact of an increased biomass use on agricultural markets, prices and food security: A longer-term perspective', paper prepared for the International symposium of Notre Europe, 27-29 November, Paris.

UN (United Nations). 2004. *World population prospects: 2004 revisions*. New York: United Nations.

UNEP (United Nations Environment Programme). 2007. Global Environmental Outlook (GEO4): Environment for Development. UNEP.

APPENDIX: FIGURES AND TABLES

Figure 1: The interrelationships between key drivers of change in food systems and their connection to human well-being

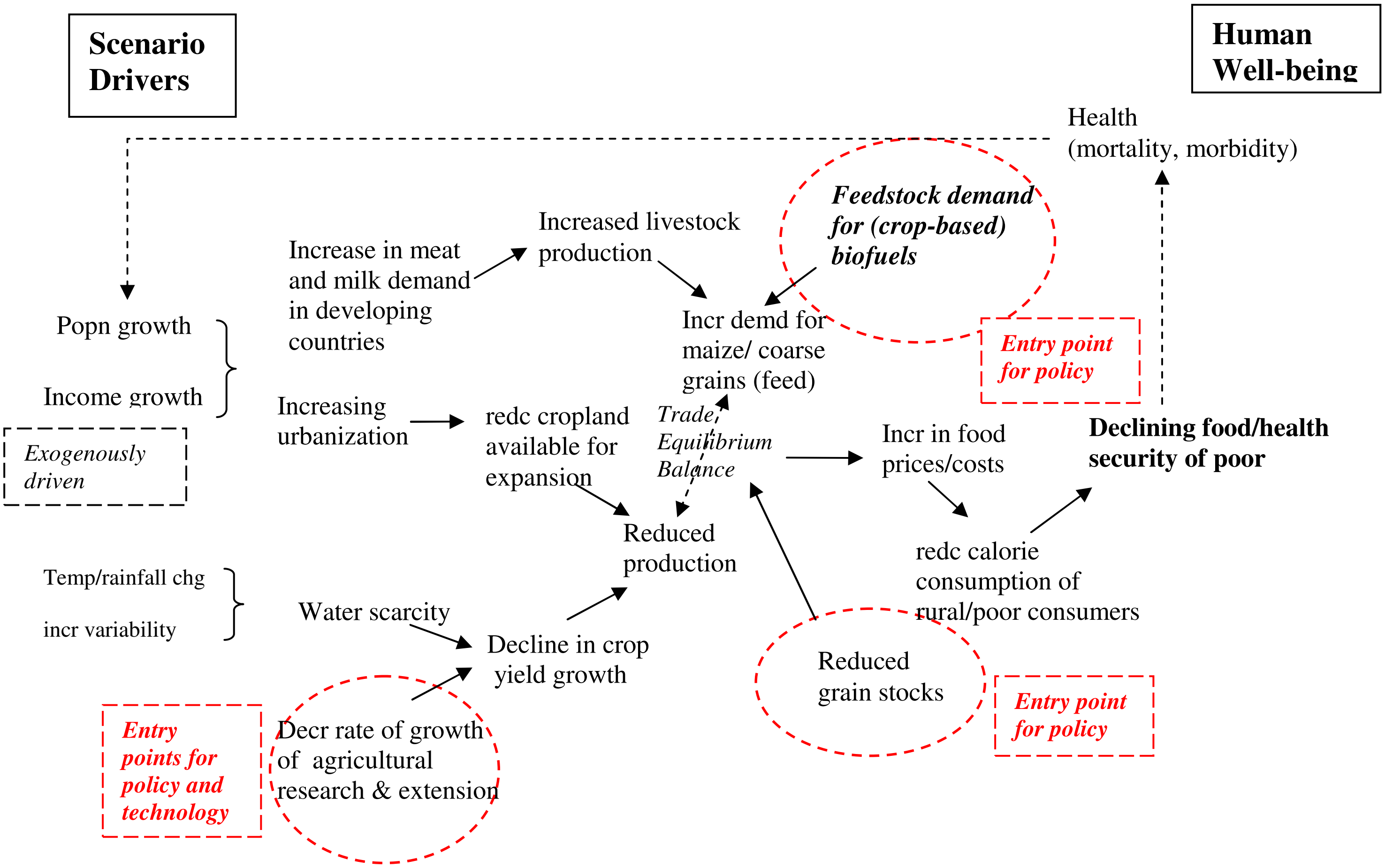


Figure 2: Characteristics of various drivers of change in food systems

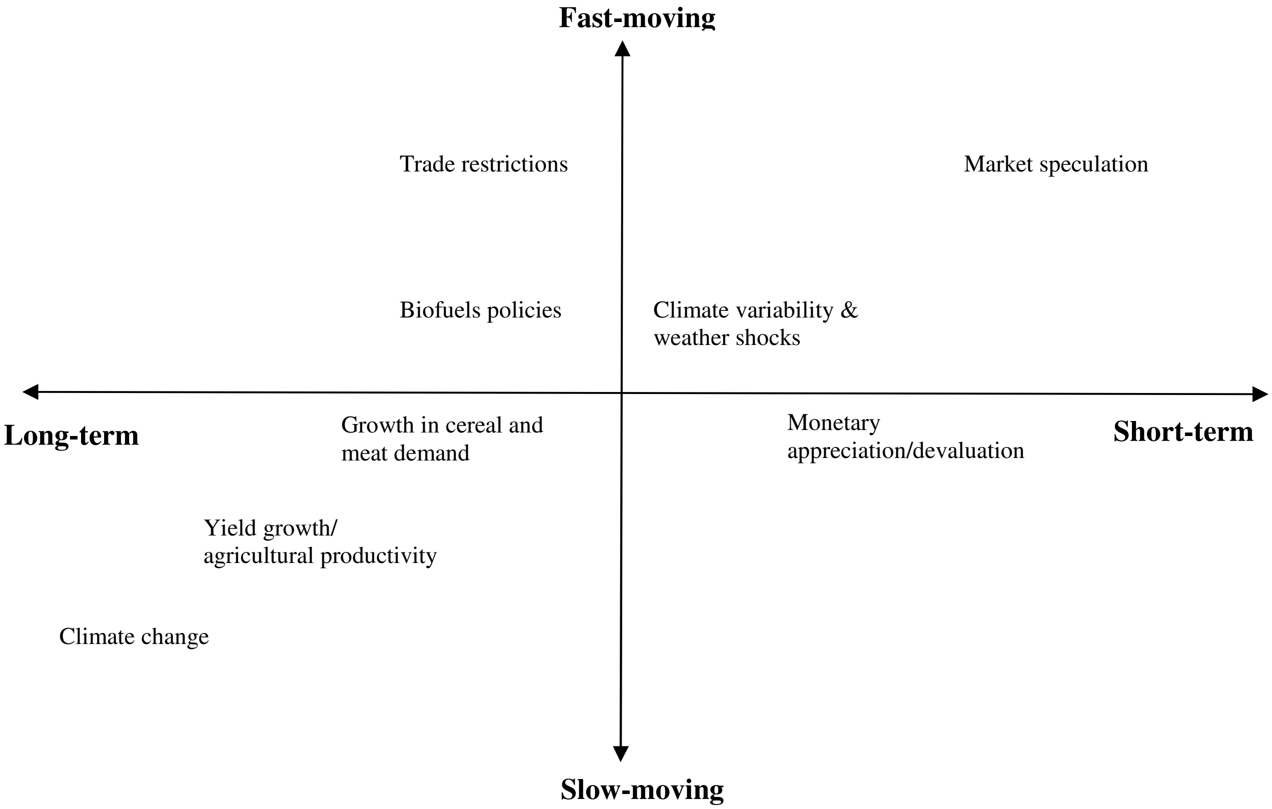


Figure 3: Key entry points for policy and investment used in modeling

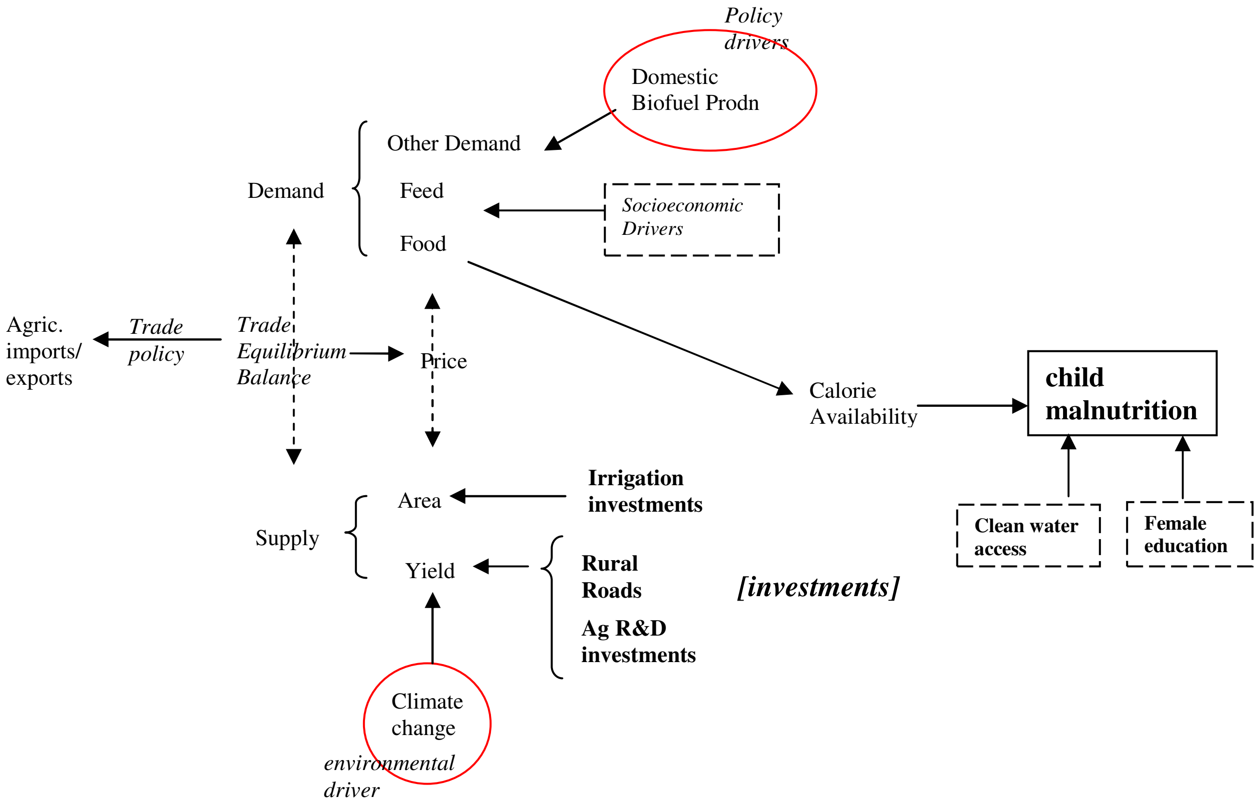
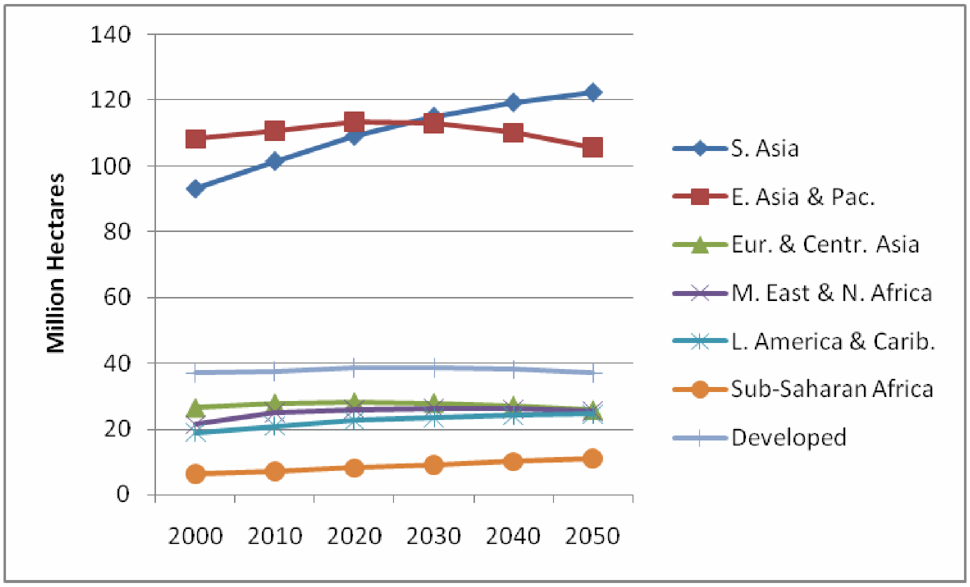
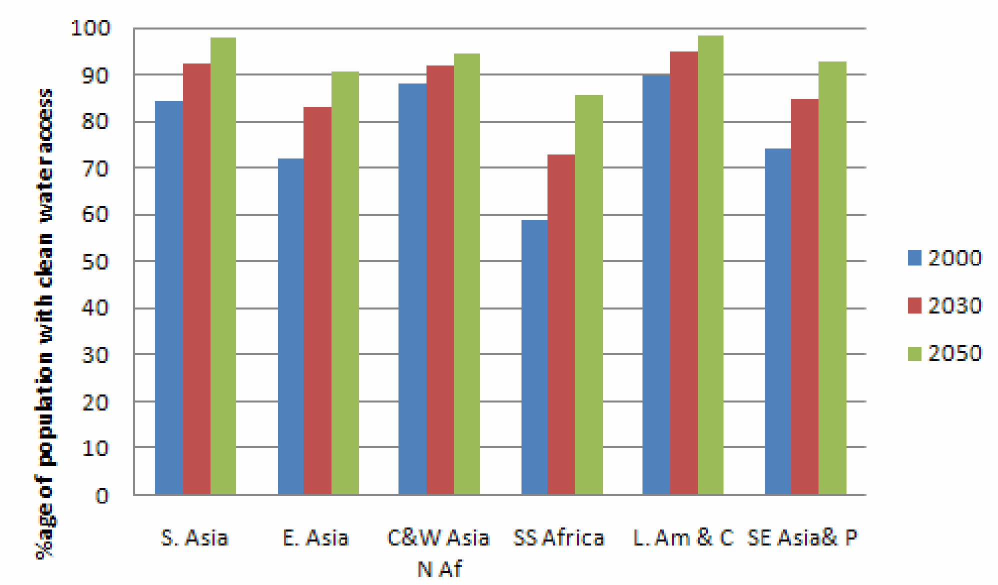


Figure 4: Simulated increases in net irrigated area over time



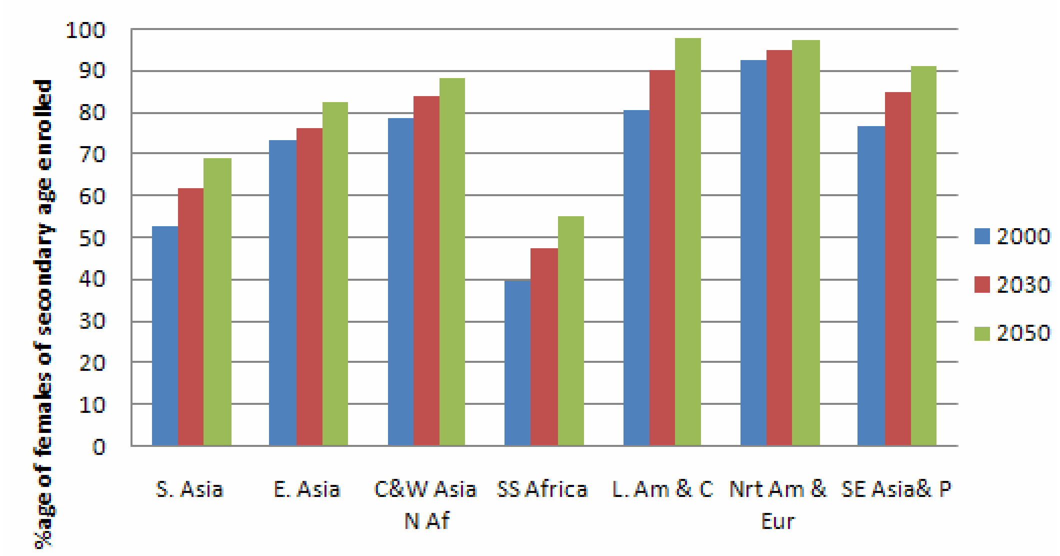
Source: IFPRI IMPACT projections.
Note: S Asia = South Asia, M. East & N. Africa = Middle East & North Africa, L. America & Carib. = Latin America & the Caribbean, E. Asia & Pac. = East Asia & Pacific, Eur. & Centr. Asia = Europe and Central Asia.

Figure 5: Share of population with access to clean water over time



Source: IFPRI IMPACT projections
Note: SS Africa = Sub-Saharan Africa, S Asia = South Asia, L. Am & C = Latin America & the Caribbean, E. Asia = East Asia, SE Asia & P = Southeast Asia and the Pacific, C&W Asia N AF= Central & Western Asia and North Africa.

Figure 6: Female secondary schooling rates over time



Source: IFPRI IMPACT projections.

Note: SS Africa = Sub-Saharan Africa, S Asia = South Asia, L. Am & C = Latin America & the Caribbean, E. Asia = East Asia, SE Asia & P = Southeast Asia and the Pacific, C&W Asia N AF= Central & Western Asia and North Africa.

Table 1: Public expenditures in agriculture-related research, 1981-2000

Region/Country	Expenditures as a % of Agricultural GDP			Public agricultural R&D spending (2005 PPP dollars, millions)		
	1981	1991	2000	1981	1991	2000
Low and Middle Income Countries	0.56	0.56	0.55	6,049	8,310	10,119
Sub-Saharan Africa	0.86	0.76	0.65	1,084	1,253	1,239
Asia and Pacific	0.33	0.37	0.39	1,971	3,287	4,758
Latin America and Caribbean	0.91	1.08	1.19	2,274	2,697	2,710
Middle East and North Africa	0.60	0.60	0.74	720	1,074	1,412
High Income Countries	1.51	2.08	2.35	9,774	12,577	13,313
Total	0.91	1.00	0.98	15,823	20,887	23,432

Source: ASTI (2009)

Table 2: Baseline results for agricultural and non-agricultural sector investments for the years 2000-2050 (billions of 2000 US dollars)

	Agricultural Research	Clean Water	Education	Irrigation Expansion	Irrigation Efficiency	Rural Roads
South Asia	25	63	24	36	30	10
East Asia and Pacific	35	45	20	6	19	43
Europe and Central Asia	30	5	1	1	4	2
Latin America and Caribbean	58	27	6	8	11	65
Middle East and North Africa	21	13	4	5	1	2
Sub-Saharan Africa	21	66	16	44	5	112
All Developing	190	219	72	99	70	235

Source: IMPACT model projections

Table 3: Breakdown of agricultural sector investment needs under baseline case for the years 2000-2050 (billions of 2000 US dollars)

	Total Agricultural Spending	Share of Total Agricultural Spending			
		Agricultural Research	Irrigation Expansion	Irrigation Efficiency	Rural Roads
South Asia	101	24%	36%	30%	10%
East Asia and Pacific	102	34%	6%	19%	42%
Europe and Central Asia	38	80%	3%	11%	5%
Latin America and Caribbean	142	41%	6%	8%	46%
Middle East and North Africa	29	74%	16%	2%	9%
Sub-Saharan Africa	182	12%	24%	2%	62%
Developing	593	32%	17%	12%	40%

Source: IMPACT model projections

Table 4: Additional spending needs for agricultural sector to offset climate change impacts

Breakdown of Total Spending in Agriculture (billions US $)

	Agricultural Total	Agricultural Research	Irrigation Expansion	Irrigation Efficiency	Rural Roads
South Asia	78	10	14	35	19
East Asia and Pacific	52	10	2	29	11
Europe and Central Asia	13	6	-	7	0
Latin America and Caribbean	62	12	3	13	35
Middle East and North Africa	16	12	-	3	4
Sub-Saharan Africa	171	15	12	7	138
Developing	392	65	30	93	208

Increase in spending over baseline levels

	Agricultural Total	Agricultural Research	Irrigation Expansion	Irrigation Efficiency	Rural Roads
South Asia	78%	43%	38%	115%	190%
East Asia and Pacific	50%	29%	30%	151%	26%
Europe and Central Asia	33%	21%	0%	157%	19%
Latin America and Caribbean	44%	21%	35%	116%	53%
Middle East and North Africa	56%	55%	0%	638%	178%
Sub-Saharan Africa	94%	69%	27%	146%	123%
Developing	66%	34%	30%	133%	89%

Source: IMPACT model projections