Joint Working Party on Agriculture and the Environment

MODELLING ADAPTATION TO CLIMATE CHANGE IN AGRICULTURE

Contact person: Ada IGNACIUk (email: ada.ignaciuk@oecd.org)

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EXECUTIVE SUMMARY

Issues at stake

For centuries, the global food system has been evolving and adapting to changes. In recent decades, the agriculture sector was able to keep up with growing demand for food and fibre. However, a key concern rises whether the agricultural sector will be able to produce enough food at affordable prices when the population will reach 9 billion people. Additionally, global agricultural production may be hampered by progressive climate change.

Whether these changes will pose a risk of insufficient food supply resulting in higher food prices will depend on the direction and magnitude of climate change and also on the adaptive capacity of the agricultural sector. Adaptation strategies, such as the introduction of new varieties that are better adapted to new climatic circumstances, or strategies to supply irrigation water in regions increasingly exposed to droughts may mitigate some of the negative impacts of climate change and contribute to reap additional benefits where possible. Open trade in agricultural goods and technologies can also contribute to widespread availability of affordable food.

Methodology

Model-based scenario analysis can shed some light on how climate change may affect future agricultural prices, consumption patterns, trade and the use of natural resources. The study uses the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). In contrast to most other agri-economic models, IMPACT represents the climate- and water-related aspects in agriculture by linking a highly disaggregated partial equilibrium model with a water basin management model.

Some adaptation actions may be costly to implement. Estimates of costs of adaptation in agriculture are scarce in the literature; therefore, this report presents some cost estimates of developing new varieties (both public and private R&D) and of implementing additional irrigation improvement technologies for OECD countries. The approach to assess adaptation costs used in this study is based on a methodology developed by the World Bank (2010).

Main results

The paper investigates long-term scenarios for agricultural production and how this is affected by the impacts of climate change. It focuses on the projections for yields, food availability and prices, and land use change. These long-term projections are then used to get a first glance at the possibilities to assess selected adaptation strategies and related costs. The aim of the study is threefold: (i) to analyse the potential impacts of climate change on the agricultural sector, (ii) propose adaptation strategies and measures to reduce the negative impact climate change might impose on the agricultural sector and (iii) provide some estimates of adaptation costs for the OECD countries.

The numerical results from simulations with the IMPACT model imply that, by the middle of the 21st century, even without climate change impacts, prices of agricultural commodities will be higher compared with current levels. This increase is projected to be primarily driven by increased demand for food due to population and income growth, more protein-rich diets and increased demand from the energy
sector. Future potential extensification of agriculture may be hampered by increased competition for land for human settlements, industry and conservation of natural areas. Despite an ongoing increase in agricultural productivity, under current policy settings, by 2050, the real prices of rice and wheat could increase by about 25%, whereas the real price of maize, an important food and feed crop, may increase by 50%, compared to 2005.

While quantitative effects depend crucially on the specification of the model, qualitative results indicate that the impacts of climate change on agriculture, in terms of yields, would be negative for most countries and commodities. Results imply that the impacts of climate change are unevenly spread across the world, including across OECD countries. Despite this heterogeneity and large uncertainties of such projections, all investigated model projections point to a potential decrease in average yields of the major crops globally. For instance, on average, projected yields of maize, wheat and rice are estimated to decline by 10%, 7% and 6%, respectively, due to climate change. At a regional level, as much as a quarter of potential yields may be foregone due to climate change, e.g. as observed in the case of maize in North America or wheat in Australia. Climate change influences the world price levels of all agricultural commodities; real prices of maize, rice and wheat are likely to further increase by up to 30% in the most extreme climate scenario.

Climate change is likely to affect the poorest populations the most and to increase food insecurity in many regions. In particular, the number of malnourished children in Sub-Saharan Africa would be expected to increase with the severity of climate impacts. Other regions in Asia and North Africa are sensitive to progressive climate change as well.

The model implies that adaptation can play an essential role in limiting some of these negative consequences (and stimulating positive impacts where applicable). Autonomous adaptation measures such as altering inputs to agricultural production, e.g., choosing more appropriate seed varieties to new climate conditions, improving on-farm water retention in soils or altering the timing of cropping activities are important to increase the resilience of food systems. Although it is crucial that such ‘no-regrets’ strategies continue to be implemented, these ‘good practices’ may not sufficiently reduce future climate risks. Additional adaptation measures may be necessary to offset some of the remaining climate damages. Among these measures, this document focuses on (i) development of crop varieties better adjusted to new conditions, (ii) technology transfer, (iii) irrigation efficiency improvement, or (iv) irrigation extension.

Extreme climate events, such as droughts or heat waves, are likely to occur more frequently. Therefore, the strategic development of new breeds of crops and livestock should be more robust to fit a wide range of climate conditions and resource efficiency objectives. The model implies that adopting such varieties in the United States could reduce world prices of maize and wheat in 2050 by 3% and 1%, respectively. When such varieties are implemented in all OECD countries, the positive effect of yields improvement is larger; the world price of maize and wheat may decrease by 4% and 2%, respectively. Also the price of livestock is reduced due to cheaper feed. Increased productivity in maize and wheat also decreases pressure on land.

By mid-century, projections imply that the demand for agricultural land use and water will increase globally. Therefore a second specific adaptation policy measure to reduce climate risks would be to support an improvement in irrigation systems. The use of pressurised irrigation systems, in particular, decreases water demand by the agricultural sector and increases the efficiency of resource use. As such, highly efficient irrigation systems decrease climate risks and primarily during droughts they may prevent large yield losses on irrigated land.

Investment in systems that use water more efficiently may benefit other sectors in the economy, when the ‘saved’ water is used outside of the agricultural sector. It may also increase the life-time of aquifers, or
directly profit a farmer who may expand his/her irrigated fields. Unless other water regulatory mechanisms exist, farmers often use the additional water to increase the production of food. If the ‘saved’ water is utilised to expand irrigation, newly available land is converted to high-profit commodities. Under the irrigation management scenarios, the observed price decreases are broadly spread: between 1.5 and 3% for maize, rice, potatoes, and vegetables.

Because climate impacts differ regionally, investments in local and international infrastructure may help to facilitate trade both domestically and internationally. This would help diversify sources of supply and smooth the risks associated with climate change. Trade may help offset the economic consequences of the most harmful impacts of future extreme climatic events.

The overall costs of adaptation are likely to be substantial if no mitigation actions are undertaken and current trends of emissions continue. Moreover, the adaptation costs are likely to increase with time. The costs depend strongly on the required adaptation level. It may not be economically efficient to fully offset climate damages by investing in very costly adaptation options. Due to the lack of common measures of adaptation and hence evaluations of the cost-effectiveness of specific adaptation measures, it is difficult to determine optimal adaptation strategies.

Although the modelling framework used in this analysis is not capable of assessing the cost-benefit ratio of the investigated adaptation measures, the estimates of potential additional costs in R&D and in improved irrigation technologies together amount to USD 16-20 billion p.a. by 2050 for the OECD countries. These estimates are in the middle of the range of existing cost estimates for developed countries. Part of these costs may be carried out by the private sector, creating investment opportunities. The private sector is already increasing its share in agricultural R&D and it appears likely that by 2050 private R&D will be larger than public R&D.

To conclude, climate change will likely have a significant, mostly negative, effect on future crop yields by mid-century. In order to limit some of the negative consequences, it may be necessary to go beyond what is currently known as autonomous adaptation. This report shows, in particular, that developing improved seed varieties, transfer of technologies, and improved irrigation systems can make agriculture more resistant to changing climate conditions. Access to new technologies can help secure global food availability. Similarly, increasing the efficiency of irrigation systems or expanding irrigation infrastructures, where appropriate, can significantly reduce water stress and make farming practices more resilient. Those changes need, however, substantial investments that increase over time with every tonne of CO₂ emitted.
MODELLING ADAPTATION TO CLIMATE CHANGE IN AGRICULTURE

1. Introduction

For centuries, the global food system has been evolving and adapting to changes. However, agriculture is confronted with increasingly restrictive constraints to supply adequate and affordable quantities (Tilman et al., 2011; OECD/FAO, 2012). This is a result of an increasing global population, changing diets, and additional demands for land due to bioenergy and sequestration policies, urbanization, and other drivers. Moreover, ongoing soil degradation, water depletion and the decreasing capability of ecosystems to sustain their functions increase the challenge of sustainable food production. Climate change is already starting to add further pressure to the level of agricultural production and is expected to become more important in the future (Lobell et al., 2011; Foley et al., 2011; Foresight, 2011).

With current policies, depending on the severity of the climate change scenario, by 2050, the global loss of agricultural productivity is expected to be in the range of 5-20% (Cline, 2007; Parry et al., 2007, Nelson et al, 2014, IPCC, 2014), with the largest decrease in productivity in the least developed countries. Climate change can, however, also generate benefits for some agricultural sectors in certain regions. For instance, some developed countries in the northern hemisphere can potentially gain from longer vegetation periods, possibilities of growing more profitable crops and a possible, though highly debated, CO₂ fertilization effect (Challinor et al., 2009; Peltonen-Sainio, 2012). Scenario analysis can shed further light on how important these different interactions are.

The current paper investigates long-term scenarios for agricultural production and how this is affected by the impacts of climate change. It focuses on the projections for yields, food availability and prices, and land use change. These long-term projections are then used to get a first glance at the possibilities to assess adaptation to climate change. The aim of the study is threefold; (i) to analyse the potential impacts of climate change on the agricultural sector, (ii) propose adaptation strategies and measures to reduce the negative impact climate change might impose on the agricultural sector and (iii) provide some estimates of adaptation costs for the OECD countries.

This work builds on two previous OECD reports: “Economic Aspects of Adaptation to Climate Change – Cost Benefits and Policy Instruments” (OECD, 2008) and “Climate Change and Agriculture – Impacts, Adaptation and Mitigation” (OECD, 2010a). Both reports underline the importance of building adaptive capacity to reduce the negative impacts of actual or expected climate change. OECD (2008) focuses on sectoral estimates of climate change impacts, though it does not focus specifically on agriculture, while OECD (2010a) focuses mainly on agriculture but does not provide quantitative information on impacts and adaptation.

Most studies that concentrate on the climate change impact on agriculture analyse the direct impacts of temperature change on yields and only a few include a water component, although, in several regions, the availability of water is already the limiting factor for agricultural production. For a full picture of climate impacts on agriculture and the related adaptation measures, it is therefore necessary to include the impacts of potential water stress in the long term.

The study uses the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), developed by the International Food Policy Research Institute (IFPRI), as this model has a
comparative advantage in representing the climate- and water-related aspects in agriculture, compared to other agri-economic models. The analysis is undertaken in a global context with a detailed regional disaggregation, and with explicit attention to the OECD countries where possible.

This paper is structured as follows. Section 2 discusses global food availability in the long term agricultural scenarios. Section 3 elaborates on various socio-economic assumptions. In particular, it presents the modelling results of the impacts of an alternative set of socio-economic assumptions. Some modelling results of the impact of climate change on prices of various agricultural commodities, yields, and land use allocation are shown in Section 4. Additionally, some results are presented on how these assumptions may impact key indicators of food security. Several adaptation measures that aim to mitigate potentially negative impacts of climate change are discussed in Section 5 and 6, including their potential impacts on agricultural production and food security. Section 7 presents some estimates of adaptation costs including additional public and private R&D expenditures and additional investments in water management system in order to offset some negative impacts of climate change. Section 8 concludes.

2. Global food availability in the long term scenarios

Several factors shape the future of agricultural sectors. The demand for food depends, among others, on population growth, the composition of diets and income levels. Supply of agricultural goods is to a large extent determined by biophysical conditions that crops and livestock are exposed to, but also by socio-economic developments and agricultural and (bio) energy policies.

In the last decades of the twentieth century, a trend of decreasing real agricultural prices was observed. This trend was disrupted by the agricultural price spikes of 2008, 2010 and to a lesser extent 2012, due to various reasons, including major droughts, bioenergy policies, and price increases of inputs. According to the Agricultural Outlook 2013-2022 it is expected that for the next decade prices of crops and livestock will remain at high levels (OECD/FAO, 2013). Prices of grains are expected to oscillate around their 2013 level, but prices of oil seeds may increase towards 2020 as a result of increased demand from food and energy sectors. Due to increased demand for meat, the price of livestock is also pushed upwards. Such short and medium term projections depend strongly on economic and policy developments, however, while long term scenarios for agriculture focus more on underlying trends, not least those related to the natural resource and possible climate constraints.

There is by no means consensus with regard to assessing the possible direction of agricultural price developments by 2030-50. Some studies indicate further decreases of crop prices and some indicate possible sharp price increases. Von Lampe et al. (2014) compare the price projections of agricultural commodities among several agricultural models under a common set of assumptions. Six out of ten models that participated in this endeavour anticipate a price increase for agricultural commodities, one model shows practically no price effects, and three models indicate a price decrease for 2050 as compared to 2005. The aggregate price index of agricultural commodities is projected to change between -15% to +37% compared to the 2005 level, for the Reference scenario (von Lampe et al., 2014).

This section sheds light on possible scenarios for agricultural markets in 2050 with explicit attention to potential consequences of climate change on food availability and focusing on OECD countries. To analyse future agricultural markets and the impact of climate change on agricultural production, the IMPACT model is used. IMPACT is linked to specific biophysical crop models and it incorporates a hydrological model to account for changes in water availability (Rosegrant et al., 2012). The schematic overview, description and some limitations of the IMPACT model can be found in Annex 1.

1. The IMPACT yield projections were chosen as the central projection for the Agricultural Model Intercomparison and Improvement Project (AgMIP) project.
Acknowledging the many uncertainties surrounding potential future socio-economic development paths and climate patterns, a choice of one scenario may be misleading. Therefore, to shed some light on the range of possible futures two different sets of ‘climate conditions’ are chosen from which one is reflecting the current climate and the second one is characterised by high climate impacts induced by continued high levels of greenhouse gas (GHGs) emissions. To reduce climate modelling bias, i.e. the differences in temperature and precipitation changes, it is important to consult the results of different climate models. Another important set of inputs for agri-economic modelling requires assumptions of crops responses to changes in precipitation and temperatures. With the same input set of climate parameters, these responses may differ per crop model due to the way these specify production processes. Various combinations of climate and crop model scenarios may thus characterise a plausible range of possible futures. The input from two crop and two climate models was used for this analysis.

Throughout the report a set of economic indicators is chosen to highlight future developments on agricultural markets. This includes world prices of various agricultural commodities, average crop yields, and land allocation. The amount of available calories per capita and the level of malnourished children (between 0 and 5 years old) are used as a proxy for food security. Where appropriate, trade patterns are also discussed. The world price level, one of the main economic indicators, reflects the changes in equilibrium on the international market and largely drives changes in trade patterns in IMPACT. Crop yields and land use changes indicate the response of farmers to changing biophysical conditions and to the price levels.

For purely illustrative purposes, the results are presented for the four aggregate regions that cover all OECD countries: (i) Australia, New Zealand and Chile, (ii) Korea and Japan, (iii) North America, and (iv) OECD-Europe. Additionally, to provide the larger context of the agricultural market developments in other parts of the world and to analyse potential food security issues, four regions that represent low-income countries and are particularly vulnerable to food insecurity are presented, namely: Sub-Saharan Africa, Middle East & North Africa, and South and South-East Asia.

2.1 Policy scenarios

The policy scenarios used for this analysis are based directly on a harmonised set of scenarios as developed in the international AgMIP project. AgMIP is a model comparison exercise focusing, among others, on simulations for future climate change conditions (von Lampe et al., 2014). Several modelling groups, with different types of crop, agricultural and economic specifications, participate in AgMIP to compare results from a harmonised set of scenarios and use the insights to substantially improve information on the impacts of climate change on agriculture and on possible adaptation and mitigation strategies. There are two main advantages in using these scenarios. First, they have been peer-reviewed. Second, when possible, additional context is provided on the impacts of climate change on agriculture in other models, keeping the same assumptions on socio-economic and climate variables.

To analyse the impact of climate change on agriculture, two crucial sources of information are needed: 1) the socio-economic characteristics, essential to specify demand side developments, and 2) information on future climate, needed to assess future yield changes and therefore changes on the supply side. Additionally, a reference scenario is needed against which the comparison of diverse options can be made to assess the magnitude of change. As the basis for this set of analysis, newly developed standardised

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2. Trade is considered a residual in the national supply and demand balance. It is considered in net terms in interacting with global markets. Countries trade with a world market, so the model does not consider differentiated bilateral trade (i.e. maize from Mexico is the same as maize from South Africa). A country is a net exporter when national supply is greater than demand, and a net importer when national supply is less than demand.
scenarios – prepared for the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) – are used. Table 1 presents a brief overview of the scenarios and their important drivers.

The socio-economic assumptions are based on the so-called Shared Socio-economic Pathways (SSPs). These include assumptions on population and GDP growth by country to 2100 (IIASA/OECD, 2013). In this report, the Reference scenario uses the assumptions that follow ‘business-as-usual’ economic and population trends based on the standardised scenario SSP2 (van Vuuren et al., 2011a). In this reference SSP2 scenario, global population reaches just above 9 billion people by 2050. The majority of the population growth is expected to take place in non-OECD countries. The combined group of OECD countries are also projected to have a larger population compared to 2010, except for the new-accession EU countries, Japan and Korea, where aging trends dominate. Overall, GDP in OECD countries is expected to almost double and global GDP increases two-and-a-half times between 2010 and 2050. There is some progress towards achieving development goals, reductions in resource and energy intensity, and decreasing fossil fuel dependency. However, there is only intermediate success in addressing air pollution or improving energy access for the poor as well as other factors that reduce vulnerability to climate and other global changes (Edenhofer et al., 2010).

Table 1. Overview of the scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Socio-economic characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Population and income continue to grow at ‘business-as-usual’ trends – SSP2</td>
<td>Climate conditions resemble weather patterns of the last 50 years.</td>
</tr>
<tr>
<td><strong>Alternative socio-economic scenarios</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternative SSP</td>
<td>Low population growth in the OECD countries, moderate income, high income inequalities between OECD and non-OECD countries – SSP3</td>
<td>As Reference</td>
</tr>
<tr>
<td><strong>Alternative climate scenarios</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 1</td>
<td>As Reference</td>
<td>future climate RCP 8.5 calculated by IPSL; impacts on crops calculated using LPJmL crop model</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>As Reference</td>
<td>future climate RCP 8.5 calculated by Hadley; impacts on crops calculated using LPJmL crop model</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>As Reference</td>
<td>future climate RCP 8.5 calculated by IPSL; impacts on crops calculated using DSSAT crop model</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>As Reference</td>
<td>future climate RCP 8.5 calculated by Hadley; impacts on crops calculated using DSSAT crop model</td>
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The socio-economic assumptions play an important role in assessing future agricultural markets. For illustrative purposes, an Alternative SSP scenario with different assumptions on population and GDP growth is analysed in this report: the standardised scenario SSP3. This scenario is characterized by slow growth in the rich countries and hardly any convergence in incomes across countries and rapid population growth. Figure 1 shows the differences between these two scenarios in terms of the population and GDP/capita assumptions. In many high income OECD countries, population remains constant or even decreases compared with 2010. Globally, the declining OECD population is more than offset by the
population growth in non-OECD countries; the total population is expected to reach 10 billion people. With the exception of Canada, the GDP per capita of the OECD countries is lower than in the Reference scenario. Regions such as Sub Saharan Africa and South East Asia have about 50 and 40% lower per capita income compared to the Reference scenario respectively. The average global income per capita is 60% lower in 2050 as compared to the Reference scenario assumptions.

The climate scenarios are based on socio-economic projections that are identical to the Reference scenario assumptions (SSP2). They differ by how the global circulation models are used to interpret changes in emission concentrations into changes in regional precipitation and temperature levels. This information is used by the crop models that calculate the impact of the changing temperatures and precipitation on crops and inform the economic models about changes to the average yields under various climate assumptions.

These alternative climate scenarios assume increasing concentrations of GHGs in the atmosphere, slightly exceeding current trends to 2050, based on the so-called Representative Concentration Pathway (RCP) 8.5 (van Vuuren et al., 2011b; see also Appendix 2). For the second half of the 21st century, by assumption, emissions in the RCP 8.5 scenario exceed current emission trends substantially and result in very high GHG concentration levels, with radiative forcing reaching 8.5 W/m², resulting in an increase of global average temperature by 4 to 7 degrees Celsius. In addition, no CO₂-fertilisation effect is accounted for. This scenario can therefore be interpreted as a strong climate change scenario. On the other hand,

3. High fuel prices boost Canadian GDP in this alternative scenario.
however, other factors such as sea level rise or biotic stresses are not included, reducing some potential negative impacts.

The climate scenarios result in two future climate states based on given emissions concentration paths by two different global general circulation models (GCMs); namely IPSL and Hadley (Johns et al., 2006). These GCMs produce sets of changes in regional temperatures and precipitations averaged monthly. These scenarios differ from the reference scenario only in terms of climate change assumptions (RCP8.5 versus the projection based on last 50 years). The assumptions on which they are based are used subsequently to feed two different crop models, LPjml and DSSAT. Each of these models calculates the yield effect associated with biophysical changes induced by specific sets of temperature and precipitation. The combination of the climate and crop models result in four alternative, entitled climate scenarios 1-4, as shown in Table 1. Since all other assumptions are kept the same as in the Reference scenario, comparing these climate scenarios to the Reference scenario allows for the specific analysis of climate change impacts on agriculture.

3. Socio-economic impacts on agriculture

Global demographic and economic trends have an impact on how much, and what sort of food will be consumed. Whether agricultural productivity and sustainable extensification will be able to meet growing (and changing) demand will be crucial to determine future price levels of agricultural commodities. A wealthy population demands on average more nutritional and caloric food. Therefore, if the future income level is expected to increase and the middle class grows, prices of higher value crops, dairy product and meat may reach a higher plateau. Additionally, with an increase in education and income levels, it may be expected that environmental awareness increases as well. Some environmentally friendly technologies, including sustainable intensification of agriculture, organic methods of production and agroforestry, may additionally increase production costs which would translate in higher food prices. But also more investments in the sector may take place, resulting in more efficient and more sustainable production, and consequently in higher agricultural productivity. Increased demand for ethanol and biodiesel may in the first place increase demand and price for grains and oil seeds, respectively, and indirectly increase prices for other crops via competition for land.

A more pessimistic view on the socio-economic developments may alter the future agricultural landscape and its trends. Larger but poorer populations will demand, in total, larger quantities of food and the composition of the food basket will be different. Whether such developments will have net positive impact on the environment is unclear a priori. On the one hand, the pressure to acquire new land for production purposes may imply that some nature areas, including primary forest, may be converted into agricultural land. On the other hand, the demand for rich protein food, such as red meat may be lower, substantially pushing downwards the demand for livestock products and indirectly for crops used as fodder. Obviously, in such a world, the number of undernourished people may remain high.

The following sections present the quantitative results of the scenario analysis with the IMPACT model. The results present possible futures but need to be interpreted carefully given uncertainties.

3.1. The impacts of the socio-economic assumptions on prices, yields and land use

Under the Reference scenario, prices of the majority of agricultural commodities are projected to increase by 2050 (Figure 2). This is mainly driven by an increase of demand because the global population increases by 2 billion within next half a century. An evident price increase is observable for high-protein commodities such as beef and poultry; by 2050 the price increases by 23% and 18% respectively. These results are driven mainly by an increase of a global middle class with its diet change. With higher income, on average, people tend to demand more meat and higher quality food. The large demand for meat triggers
an increased demand for feed. This has an effect on the price of maize; which increases by 38%. This large increase is also caused by an increase in demand for bioenergy. The prices of other staple crops are stable or increase modestly with the exception of wheat (which increases by 16%). Fruits and vegetables are consumed more in high income households; therefore their prices increase as well.

Following historical trends, yields improvements are expected to continue to take place although less rapidly. Globally, most of the yields improvements will be in the developing countries, especially in regions that present higher yield gaps. Millet, a crop grown mainly in Africa and India, is expected to about double its yield compared to current levels by 2050 (see Figure 2). In OECD countries, an increase in maize yields may be expected, but the yield growth is likely to be limited to about 1% on an annual basis (Figure 2). For crops like wheat and rice, modest yield increases are likely to happen in the Reference scenario.

Despite the continuous increase in yields, the pressure on land increases. In high income countries, agricultural area is expected to remain constant; however, in developing countries it is likely that the increased demand for food will increase the pressure on land and will result in extensification of agriculture. By 2050, under current policies, an additional 10-15% of land may be used for agricultural production. The trend in land use expansion is partly based on historical information and assumptions about exogenous future land use changes, including urbanization and expected changes in forested areas. Land use allocation has an endogenous component; it changes according to profit maximization.

The trends discussed above may change when different assumptions about the population growth and the wealth are made. In the Alternative SSP scenario, lower average income and higher population growth were assumed. Compared with the Reference scenario, prices of agricultural commodities are lower with some exceptions (Figure 2). Prices of staple commodities, especially those that have relatively high market shares in Africa and South East Asia, where the highest population growth is assumed, are higher under the Alternative SSP scenario. These regions experience the largest difference in per capita income. Poor households in reaction to a decreased income may reduce further the expenditures away from nutritious food, including meats and vegetables towards the basic food such as rice, millet or sweet potatoes. Prices of maize and wheat increase as well by 2050, but the increase is less pronounced than in the Reference scenario due to a substantial decrease of demand for these as feed.

In this more ‘pessimistic’ setting, exogenous yields improvements are assumed the same as in the Reference scenario. Overall, the land allocation follows the demand patterns, but a larger share of land is allocated to staple grains in the Alternative SSP (see pie charts in Figure 2). Yields are in fact lower for maize and wheat, but not dramatically lower; for both maize and wheat, yields are about 1% lower in the OECD region. In the Alternative SSP scenario, maize is used less for feed and more for direct food consumption. However, reflecting the trends of a less pronounced transition towards high-protein food in the developing countries, the demand for land for ‘staple’ food such as rice, millet, sorghum and cassava increases.
3.2. Food security

Various policies are being established in order to reduce hunger and poverty. The recent food price spikes have shown, however, that food security remains a serious concern around the world. Especially sensitive to food price volatility are Sub-Saharan Africa, South and South East Asia, and the MENA region, where a substantial share of population is food insecure. Two indicators have been chosen to shed some light on potential food security issues for these regions: (i) the availability of calories consumed per capita and (ii) the share of malnourished children (children between 0-5 years old)\(^4\).

Figure 3 shows that for virtually all regions and for both scenarios (Reference and Alternative SSP), the available amount of calories per capita increases in 2050 as compared to 2005. This also has indirect consequences on the potential number of malnourished children. The improvements in calory-availability is driven by considerable income increases in all regions, especially in the least developed countries and

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4. The methodology used for calculating the share malnourished children is based on Smith and Haddad (2000).
may increase chances of further reduction of hunger and poverty. In countries with high income inequality, such improvements may be muted. The expected income level in the Alternative SSP scenario is on average lower, therefore the benefits in terms of higher calories consumption are less pronounced.

By 2050, all regions except Sub-Saharan Africa show a reduction in child malnutrition levels in the Alternative SSP scenario. This is mainly driven by an increased income level. In the Alternative SSP scenario, the levels of malnutrition in the Sub-Saharan Africa region may increase due to significantly slower GDP growth and rapid population growth in the region. This suggests that income growth and population pressures are major constraints to achieving food security in the region.

Figure 3. Change in food consumption per capita and change in the number of malnourished children in 2050

Source: Own calculation based on IMPACT.

4. Climate change impacts on agricultural markets

Climate change will likely affect the food production both through direct and indirect ways which often create complex interactions and are hard to analyse in separation. The increase of CO₂ concentration in the atmosphere may, for instance, induce higher yields through the so-called CO₂ fertilisation effect and therefore it may improve potential productivity, but at the same time it may contribute to an increased frequency of droughts which in turn may decrease future yields. Although CO₂ concentrations may be uniformly distributed across the globe, a variation in temperature change and precipitation levels is expected among regions. Besides the inter-regional variability, the inter-annual and seasonal variability will also likely be altered. The magnitude of change is, however, highly uncertain.

Another source of uncertainty arises from the reaction of the biophysical processes to changes in temperatures and water availability. Crop yields show a strong correlation with temperature change and also with the duration of heat or cold waves, and they differ based on plant maturity stages during extreme weather events. Similarly, crops are sensitive to droughts but also to an excess of water. In an indirect way, a change of temperature and moisture may mean a change in absorption rate of fertilizers and other minerals, which determine final yields. Crop yields are likely to be affected as well by changing patterns and intensity of weeds and pests. Climate change is likely to affect the livestock sector through the feed quantity and quality but also through the frequency and severity of extreme climate events. There is very

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5. CO₂ fertilization at 369 ppm (in 2000) is taken into account. The role of CO₂ fertilization effect on increases of CO₂ levels after 2000 is not included in model specification.
limited literature available that deals with climate change impacts on livestock, although there seems to be an agreement that the livestock sector may be particularly vulnerable (OECD, 2014a).

4.1. **Climate change impacts on global prices and yields**

Climate change is likely to have a negative effect on agriculture at the global level. The prices of the main agricultural commodities are higher under climate change scenarios compared to the Reference scenario (Figure 4) as a result of lower expected yields. Prices of major grains such as maize, wheat and rice are on average 5% to 30% higher than in the absence of climate effects.

Figure 4. World price change and yield of selection of agricultural commodities in 2050 compared to Reference Scenario under different climate assumptions

![Figure 4](image-url)

Source: Own calculation using IMPACT.

Grains are, in general, vulnerable to increased heat and water stress, although grains such as millet that are intrinsically more drought tolerant may perform better than other grains. Figure 4 shows the impact of climate change on yields in 2050. For the three main crops, all 4 climate scenarios indicate potential yield decrease; of less than 7% in most cases. In Scenarios 3 and 4, the world prices of maize, wheat and rice are higher compared with the first two scenarios, as a result of larger negative climate impacts on these grains. Scenarios 3 and 4 use input from the DSSAT crop model, suggesting that this model shows larger sensitivity of grains to higher temperatures. The LPJML model, as used in Scenario 1 and 2, suggests larger related yield decreases for potatoes and vegetables.

Livestock prices show the secondary effects of climate change through the increased price of feeds. Prices of beef and poultry increase by 3-5% for Scenarios 1-4. IMPACT does not model the direct effect of heat and drought on animals nor on pasture productivity. Taking these effects into consideration would probably further augment prices.
4.2. Regional effects of climate change

The impacts of climate change on various crops naturally vary across the regions. Although climate change is expected to have a negative impact on yields in the majority of cases, in a few cases, a yield boost may be expected, as shown in Figure 5. Figure 6 presents the changes in land allocation relative to the Reference scenario.

Climate change will negatively affect rainfed yields to a greater extent than irrigated ones. On irrigated areas, the negative impact of changed precipitation and increased temperatures is reduced by the availability of irrigation water, making yields more resistant to climate variations. Irrigated crops have access to more diverse water sources including groundwater and rivers. Under rainfed agriculture, the only water available is that which the plants can access from the topsoil.

In general, Scenarios 3 and 4, based on input from the DSSAT model, show higher negative effects on grains yields on regional level. This observation is consistent with results of the AgMIP model comparison (von Lampe et al., 2014; Nelson et al., 2014). Differences between GCMs are less pronounced, even if for some regions, these models present contradictory results. For instance, for countries in southern Europe, the IPSL model shows positive changes for maize yields as opposed to negative results for simulations based on the Hadley assumptions. This can be explained by the fact that IPSL projects higher rainfall in this area as opposed to a decrease in rainfall expected by Hadley for this region. Overall, for OECD countries, Scenario 4 envisages the largest negative economic consequences of climate change impacts.

Despite the negative effects of climate on agricultural production, OECD countries remain net exporters of food in 2050. United States remains a large net exporter of maize, though it reduces exports to around half of its value in the Reference scenario. Many developing countries remain net importers of food and some increase net imports of food. For instance, under Scenario 3, India’s domestic maize and wheat production decreases and its imports increase by around 40 and 50%, respectively compared to the Reference scenario. Sub Saharan Africa remains a net food importer across all scenarios.

The potential negative effects of climate change do not imply, however, a large relocation of agricultural production by 2050. The land allocation remains similar to its current form. In the OECD countries, wheat remains predominantly produced in Europe and Australia, maize in North America and rice in Korea and Japan (Figure 6). The IMPACT model shows relatively modest impacts on land expansion in comparison to other models included in the AgMIP project. Some other models, such as ENVISAGE, AIM and GCAM, show much stronger increases in agricultural land use (von Lampe et al., 2014; Nelson et al., 2014). The majority of OECD countries have, however, limited potential to expand their agricultural area without infringing on natural areas.
Figure 5. Changes in yields of a selected set of commodities on irrigated and rainfed areas.

<table>
<thead>
<tr>
<th>Commodities</th>
<th>Irrigated</th>
<th>Rainfed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetables</td>
<td>-30%</td>
<td>15%</td>
</tr>
<tr>
<td>Rice</td>
<td>-15%</td>
<td>0%</td>
</tr>
<tr>
<td>Wheat</td>
<td>0%</td>
<td>-15%</td>
</tr>
<tr>
<td>Millet</td>
<td>-15%</td>
<td>0%</td>
</tr>
<tr>
<td>Potatoes</td>
<td>-30%</td>
<td>15%</td>
</tr>
</tbody>
</table>

- **Scenario 1**: 0% change
- **Scenario 2**: -15% change
- **Scenario 3**: -30% change
- **Scenario 4**: 15% change

Source: Own calculations based on IMPACT simulations.
Figure 6. Changes in land allocation within the OECD countries

<table>
<thead>
<tr>
<th>Country</th>
<th>2005</th>
<th>Reference</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia - New Zealand - Chile</td>
<td>43.13%</td>
<td>45.40%</td>
<td>44.70%</td>
<td>44.63%</td>
<td>43.98%</td>
<td>44.05%</td>
</tr>
<tr>
<td></td>
<td>0.41%</td>
<td>0.45%</td>
<td>0.46%</td>
<td>0.46%</td>
<td>0.48%</td>
<td>0.47%</td>
</tr>
<tr>
<td></td>
<td>1.04%</td>
<td>1.22%</td>
<td>1.22%</td>
<td>1.22%</td>
<td>1.22%</td>
<td>1.21%</td>
</tr>
<tr>
<td>Korea - Japan</td>
<td>17.33%</td>
<td>18.53%</td>
<td>18.50%</td>
<td>18.51%</td>
<td>18.45%</td>
<td>18.51%</td>
</tr>
<tr>
<td></td>
<td>0.33%</td>
<td>0.36%</td>
<td>0.35%</td>
<td>0.34%</td>
<td>0.36%</td>
<td>0.36%</td>
</tr>
<tr>
<td></td>
<td>15.13%</td>
<td>17.52%</td>
<td>17.37%</td>
<td>17.35%</td>
<td>17.06%</td>
<td>17.06%</td>
</tr>
<tr>
<td></td>
<td>2.29%</td>
<td>2.63%</td>
<td>2.63%</td>
<td>2.64%</td>
<td>2.57%</td>
<td>2.58%</td>
</tr>
<tr>
<td>North-America</td>
<td>38.91%</td>
<td>38.87%</td>
<td>34.58%</td>
<td>40.23%</td>
<td>40.06%</td>
<td>38.57%</td>
</tr>
<tr>
<td></td>
<td>32.03%</td>
<td>32.24%</td>
<td>32.24%</td>
<td>32.15%</td>
<td>32.15%</td>
<td>32.15%</td>
</tr>
<tr>
<td></td>
<td>1.97%</td>
<td>2.82%</td>
<td>2.91%</td>
<td>2.91%</td>
<td>2.85%</td>
<td>2.89%</td>
</tr>
<tr>
<td></td>
<td>25.16%</td>
<td>21.96%</td>
<td>22.81%</td>
<td>23.00%</td>
<td>22.57%</td>
<td>22.40%</td>
</tr>
<tr>
<td>Europe</td>
<td>49.33%</td>
<td>47.33%</td>
<td>47.01%</td>
<td>46.97%</td>
<td>46.22%</td>
<td>46.23%</td>
</tr>
<tr>
<td></td>
<td>0.58%</td>
<td>0.53%</td>
<td>0.54%</td>
<td>0.55%</td>
<td>0.56%</td>
<td>0.55%</td>
</tr>
<tr>
<td></td>
<td>3.60%</td>
<td>4.36%</td>
<td>4.36%</td>
<td>4.37%</td>
<td>4.35%</td>
<td>4.28%</td>
</tr>
<tr>
<td></td>
<td>35.71%</td>
<td>36.19%</td>
<td>36.76%</td>
<td>36.80%</td>
<td>37.25%</td>
<td>37.13%</td>
</tr>
</tbody>
</table>
Developing countries are likely to face even larger production impacts from climate change. Sub-Saharan Africa and Middle East & North Africa, in particular, lose potential production gains with climate change.

4.3. Climate change impacts on food security

Although the general uptake of calories increases compared to 2005 levels, and the number of children potentially exposed to hunger decreases, climate change is likely to have a negative effect on future food security. Scenarios 1-4 imply large changes of potential future yields resulting in increased threats to food security among many developing countries.

Figure 7 presents changes in calorie consumption per capita in 2050 and changes of the number of malnourished children due to climate change (compared to the Reference scenario). Aggregate consumption for all four climate scenarios decreases in all regions. The calories loss per capita in the selected regions due to climate change is between 2% to 5% compared to the Reference scenario.

Figure 7. Climate change impacts on food security in 2050 compared to Reference Scenario

Source: Own calculations based on IMPACT simulations.

5. Description of the set of adaptation scenarios

5.1. Identifying a set of adaptation options

Results have shown that the yields of many critical food crops can decrease by more than 30%, in some regions, by 2050, in the most negative climate scenarios. This has obvious impacts on food availability. To explore some of the potential adaptations that could be pursued to mitigate these negative effects, two types of scenarios have been developed. The first focuses on developing improved varieties that will be more capable of handling the negative effects of climate change, through better tolerance to heat and drought. The second considers the role of various water management strategies as adaptation scenarios. These two sets of measures are by no means an exhaustive list of possible adaptation measures, but rather illustrative, quantifiable, examples of possible adaptation actions.

Historically investments in agricultural R&D (e.g. developing new technologies that increase yields such as plant improvements) have proved to be a great success. Countries that have built national research
systems capable of producing a steady stream of new technologies are generally the ones that have achieved higher growth rates in agricultural Total Factor Productivity (TFP) (Fuglie and Wang, 2012). They also note that TFP has become the number one factor in increasing agricultural production, in contrast to other factors such as increased inputs of fertilizers or agricultural land expansion. Goldfray et al. (2010) suggest that there is a large scope for increasing crop yields through improved conventional breeding and biotechnology. Plant breeding and the use of high quality seeds will continue to enhance crop productivity gains in the future, provided that seed markets are properly functioning and farmers have access to high quality seeds (OECD/FAO, 2012). It is important, however, to note that there may be a higher cost associated with using such technologies.

Nonetheless, with a changing climate it is important to target investments towards those varieties that are able to withstand the increasing abiotic stress caused by changes in temperature and precipitation, as well as other indirect changes that future climate can cause such as changes in pest and disease patterns (Vermeulen et al., 2011). Currently, several research organizations are working on developing new or improved varieties that could increase farmers’ resilience to climate change. Privately funded research centres become more active in this field as well. One needs to be cautious, however, to maintain the genetic variations of current varieties (Hove, 2011).

Sustainable resource use is one of the key issues on the policy agenda in an increasing number of countries. Particular attention is often paid to sustainable, or efficient, water use. Because the agriculture sector demands significant amounts of fresh water, a number of policies in both developing and developed countries target an efficient use of irrigation water. A strong call to recognize the importance of improving the efficiency of water and soil use in a sustainable manner by the agricultural sector was made by the G20 leaders and G20 Agricultural Vice Ministers during the meetings in May and June 2012. Since then, the OECD and several other international organizations have identified a set of policy recommendations including, among others, the recognition of investments in: a) efficient water use in agriculture and b) water supply infrastructure. These are discussed in more detail in Annex 2.

Each of these general adaptation measures (research and development and water management) presents many uncertainties. Therefore a couple of different scenarios were designed to analyse some of the potential challenges and impacts of various assumptions. Table 2 summarizes these adaptation scenarios that will be discussed in more detail in the following subsections. Each scenario is based on the Reference and four climate scenarios (Scenario1-4) discussed in previous section. Together 25 adaptation scenarios are proposed; for instance, the R&D adaptation measures are applied for the Reference scenario and for Scenarios 1-4.
Table 2. Overview of adaptation scenarios

<table>
<thead>
<tr>
<th>Adaptation Scenarios</th>
<th>Description</th>
<th>Measure Specification</th>
<th>Regions and Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Research and Development</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Improved production technologies for maize and wheat are implemented in the United States. These improvements, including e.g. crop improvement and protection technologies, when adopted lead to 10% and 5% yield improvements on maize and wheat respectively in relation to standard model assumption.</td>
<td>Improved technologies begin to be adopted in the United States in 2020, reaching a maximum adoption level of 80% by 2030.</td>
<td></td>
</tr>
<tr>
<td>TT</td>
<td>Technology Transfer – Follows the R&amp;D scenario with technology diffusion from the United States to other OECD countries.</td>
<td>As R&amp;D1 for the United States. Adoption beginning in the rest of the OECD member countries in 2023 and reaching maximum adoption of 80% in 2033.</td>
<td></td>
</tr>
<tr>
<td><strong>Water Management Scenarios</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EFF</td>
<td>Irrigation Efficiency - Improvement of irrigation technology in the OECD area leading to increased water use efficiency until all basins in the OECD reach a minimum efficiency of 72%.</td>
<td>Efficiency improvements begin in 2006 and end by 2050 in all OECD countries.</td>
<td></td>
</tr>
<tr>
<td>IR</td>
<td>Irrigation Expansion – Transformation of rainfed areas into irrigated areas in OECD countries representing investments in expansion of irrigation infrastructure.</td>
<td>Irrigated area expansion grows at the same rate as basin efficiency in the EFF scenario.</td>
<td></td>
</tr>
<tr>
<td>EFF+IR</td>
<td>Combines the basin efficiency improvement of Irrigation Efficiency with the Irrigated Area expansion.</td>
<td>Combines scenarios EFF and IR.</td>
<td></td>
</tr>
</tbody>
</table>

5.2. Modelling Research and Development

Two specific adaptation measures related to research and development are proposed and discussed in this section: i) research and development (R&D) to generate improved crop production technologies in agriculture, and ii) technology transfer. These have been identified as important for reducing potential negative impacts of climate change on agriculture (OECD, 2008; EEA, 2009; OECD, 2012a). It is important to mention that the autonomous adaptation responses that result from cost-minimisation by farmers are already taken into account by the crop models used in this analysis. Specifically, crop management techniques such as changes in cropping season, changes in management techniques and choice of crop varieties are assumed to be available to farmers and thus implemented in an optimal way in the scenarios. Without these autonomous measures the impacts of climate change on yields would be higher.

To analyse the impact of newly developed varieties of maize and wheat that in the long term lead to higher growth rates of yields, a new (hypothetical) technology is introduced that increases the yield by around 10% for maize and by around 5% for wheat, compared to their traditional alternatives in the United States. It is assumed in the model that for farmers it is a cost-neutral technology; however in reality such plant improvement technologies may bear a higher seed costs compared to traditional farming
technologies. As a caveat, research costs related to this new technological development are not accounted for in the model; there are no costs associated with the new technology, i.e. its development will therefore not be at the expense of other technology development or government expenditures. These new varieties enter the United States market in 2020 and slowly increase their share compared to conventional technologies (Figure 8). The adaptation potentials of these new technologies are tested under the 5 scenarios (Reference, Scenario 1-4). It is assumed that the new technologies achieve a maximum of 80% adoption after 10 years. Figure 8 shows the technology adoption rate of the new varieties.

![Figure 8. Rate of the technology adoption in the United States over time](image)

To investigate the role that transfer of technologies can play in adapting to climate change, a second set of adaptation scenarios includes the spill-over of the new technologies for maize and wheat to the rest of the OECD countries. This adaptation scenario presents the same penetration rates in the United States as in Figure 8, but adding technology adoption in the rest of the OECD beginning in 2023, allowing for a couple of years before technology diffusion begins. The adoption rate in the rest of the OECD follows the same path as in the United States with the only difference being that adoption begins in 2023 instead of 2020. Figure 9 shows the 2 regional adoption pathways. Please note that the technology transfer apart of the ‘learning’ aspect bears also some costs.

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6. Section 7 will discuss adaptation costs separately.
5.3. Modelling water management strategies

Yields on irrigated land are on average higher than on rainfed land, which makes expanding irrigated agriculture a promising policy in response to greater demand for food, and relatively greater stresses on production from climate change. However, freshwater is not an infinite resource, and as such the expansion of irrigation although an important potential adaptation measure will need to be implemented with care due to potentially greater water scarcity associated with greater demands for water from the non-agricultural sectors, and changes in precipitation patterns due to climate change (OECD, 2014a and b).

Two irrigation policies have been identified as potentially beneficial to the agriculture sector. First, increased irrigation efficiency7 improves the use of current and future water supply. Such improvement is modelled under a scenario where all of the basins in the OECD region achieve at least 72% efficiency by 2050. A 72% efficiency level is higher than the current average in the OECD, but below the maximum observed level (Figure 23). This efficiency gain is applied linearly over the 45 year projection period, representing a slow but steady increase in irrigation efficiency. It should be noted that improved irrigation efficiency can lead to improved yields only under circumstances of water shortage. It is a technology that can be yield increasing, but is primarily focused on increasing water reliability and reducing the risks associated with water scarcity.

The second irrigation policy to be explored is the conversion of rainfed area to irrigated area. Irrigating rainfed areas is expected to lead to higher average yields, acting as a change in production technology and greater intensification. The amount of area converted to irrigation was calculated to match

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7. Irrigation efficiency equals the share of water that is effectively used by the crops to water withdrawal for irrigation.
the improved water reliability gained in the first irrigation scenario, i.e. the ‘saved’ water due to an increase of efficiency determined the conversion rate.

The expansion of irrigated areas is bound to have more direct effects on average crop yields than increased irrigation efficiency. However, due to water constraints in some regions irrigated yields may be stressed due to greater demand for water. Figure 10 summarizes the exogenous assumptions on the area transformation in the OECD region, where total area is held constant at 2005 levels, but the ratio between irrigated and rainfed areas is changed. In many OECD regions there are limited amounts of irrigated area to begin with. Percentage changes in irrigated areas can be significant due to low starting values to provide context to the magnitude of the area transformation the accompanying percentage change in rainfed areas is also included.

**Figure 10. Assumptions on agricultural land-use by 2050 in the OECD under IR scenario**

The advantages of improved irrigation are relatively small in terms of a contribution to increased food production. However when combined with irrigation expansion the benefits are expected to increase, as irrigation expansion without improvements in irrigation efficiency would lead to increased water stress. The third irrigation scenario is designed to test the interaction effects of irrigation efficiency and irrigation expansion.

6. **Results of the modelling of adaptation scenarios**

6.1. **Impacts of adaptation measures on yields, prices and land allocation**

Under both the R&D and TT scenarios, significant yield increases are observed in the adopting regions, but there are also international spill-over effects. World prices for maize and wheat decrease by 3% and 1% respectively when the improved varieties are only adopted in the United States, and by 4% and 2% respectively when adopted throughout the OECD (Figure 11).
Under the irrigation technology scenarios, there are limited yield benefits from improved water efficiency in most of the OECD countries, except in the Mediterranean basin in Southern and Western Europe (namely France). For those regions that are currently battling with water stress, e.g. the Mediterranean, irrigation efficiency measures contribute to improved yields on irrigated areas mainly maize and vegetable in the order of 3-5%. The water stress becomes more apparent when irrigated areas are expanded without increasing irrigation efficiency. Further expansion of irrigation without additional improvement of irrigation efficiency results in lower average yields in Southern and Western Europe (and North American vegetables) due to increased water scarcity for irrigation. In all other regions the expansion of irrigation leads to greater productivity as agriculture production benefits from larger shares of more productive irrigated areas. When improved efficiency is coupled with irrigation area expansion, agriculture can further benefit from the transformation to irrigation, as the reduced demand for water per hectare reduces the constraints on water use. Figure 11 illustrates the yield effects in the OECD for all 5 of the adaptation scenarios.

In all adaptation scenarios, the yield increases lead to a reduction of world prices of the main crops (Figure 12). The largest price decreases for any specific commodity occurs in the research and development scenarios, which are targeted specifically at maize and wheat. The price decreases for maize are over 4% in the technology transfer scenario, where the largest targeted exogenous yield assumption occurs. While the largest single individual price change occurs under the R&D scenarios, the indirect effects to other commodities are very limited, with price reductions in other commodities in the order of 0.25 and 0.5%. Under the irrigation management scenarios the observed price decreases are more broadly spread with price decreases between 1.5 and 3% for maize, rice, potatoes, and vegetables. Under all adaptation scenarios the effects on livestock prices are relatively modest, although the larger price decreases in maize under the research and development scenarios allows for a slightly larger price reduction (still less than 0.5%) for beef and poultry in the technology transfer scenario, because of a decreased cost of feed.
Figure 11. Average yield change by 2050 due to adaptation scenarios

AUS-NZL-CHL

-5%  5%  15%  25%

Kor-Jap

-5%  5%  15%  25%

North America

-5%  5%  15%  25%

Northern Europe

-5%  5%  15%  25%

Southern Europe

-5%  5%  15%  25%

Western Europe

Vegetables

-5%  5%  15%  25%

Potatoes

-5%  5%  15%  25%

Millet

-5%  5%  15%  25%

Wheat

-5%  5%  15%  25%

Rice

-5%  5%  15%  25%

Maize

-5%  5%  15%  25%

Reference  Scenario 1  Scenario 2  Scenario 3  Scenario 4
These changes in yields and prices have important endogenous effects on land allocation, with changing planting patterns occurring over time in response to changes in productivity and prices. With increased productivity, more can be produced using the same amount of land. Specific adaptation technologies favour certain crops over others, which leads to larger price changes, which in turn affects demand.

Figures 13-15 illustrate the effects of price on land allocation in the two most positive adaptation scenarios (technology transfer, and irrigation extension combined with irrigation efficiency increase). Under the research and development scenarios the area under maize and wheat cultivation decreases around 1%. Less area is needed to meet demand for maize and wheat, and this newly available land is converted to other commodities, with increases in areas dedicated to rice, millet, potatoes, vegetables and other crops. Under the irrigation scenarios, the adaptation measures are not specifically targeted to a single crop. They can therefore positively affect a larger number of commodities benefiting more from irrigation like maize, rice and vegetables. The production of these commodities increases. Nevertheless, the total allocation of land remains fairly steady in the adaptation scenarios, which should be expected as the relative price changes due to the adaptation measures should not lead to dramatic changes in land allocation.
Figure 13. Comparing changes in areas for select commodities in the OECD from TT scenario.
Figure 14. Comparing changes in areas for select commodities in the OECD from EFF+IR scenario.
Figure 15. Comparing changes in areas for select commodities in the OECD for TT and EFF+IR scenarios

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>Scenario1</th>
<th>Scenario2</th>
<th>Scenario3</th>
<th>Scenario4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate Change</td>
<td>42.29%</td>
<td>20.85%</td>
<td>19.39%</td>
<td>19.38%</td>
<td>20.49%</td>
</tr>
<tr>
<td></td>
<td>3.53%</td>
<td>29.92%</td>
<td>30.73%</td>
<td>30.84%</td>
<td>30.77%</td>
</tr>
</tbody>
</table>

- Maize: 1.87%, 1.2%, 1.02%, 1.93%, 1.94%
- Rice: 42.81%, 42.68%, 41.6%, 20.61%, 20.31%
- Wheat: 3.59%, 3.58%, 3.54%, 3.53%, 3.55%
- Millet: 30.73%, 30.77%, 30.73%, 30.73%, 30.73%
- Potatoes: 30.3%, 30.21%, 30.17%, 30.17%, 30.17%
- Vegetables: 3.89%, 3.89%, 3.84%, 3.84%, 3.84%
- Other Crops: 3.9%, 3.9%, 3.9%, 3.9%, 3.9%
6.2. Impacts of adaptation measures on food security

Despite the impacts of climate change, it is likely that the overall food security increases in next few decades thanks to an increase of agricultural productivity in both developed and developing countries, and various policies to reduce poverty. The suggested adaptation measures in the OECD countries via the price effect may further improve the situation. Each of the adaptation scenarios implies a reduction of world food prices over the projection period. This reduction in food price increases consumers’ purchasing power, allowing them to purchase more food with the same income. Increasing food availability leads to more robust diets and decreasing numbers of malnourished children. However, the price changes that we see in the adaptation scenarios are fairly modest, which leads to small increases of food availability globally (less than 0.5%), with small improvements in malnourishment (decreasing by less than 0.5%). Thus, while these scenarios help mitigate some of the effects of climate change, they do not fully mitigate the potential food insecurity in developing countries.

Figure 16. Changes in food availability and malnutrition in adaptation scenarios

This suggests that increasing productivity in developed countries will not have significant spill-over effects in developing countries without there being larger changes in prices. More targeted measures focusing on increasing production in developing countries, as well as improving access to markets will likely have larger benefits towards reducing malnutrition globally than those focused on increasing productivity in developed countries. Figure 16 summarizes the observed changes in food availability (expressed in calories) and the resulting changes in the number of malnourished children for the adaptation scenarios.
7. Costs of adaptation

While the previous sections have illustrated the potential effectiveness of adaptation measures as a response to climate change, it is important also to investigate the adaptation costs. Existing work in the agricultural sector has focused on the potential impacts of climate change, with only a few studies assessing the costs of adaptation (OECD, 2008; 2010a). It is also challenging to compare the existing estimates of adaptation costs, due to various factors such as: differences in geographic scope, varying definitions of what adaptation costs constitute, and assumptions about the degree of autonomous adaptation. For example, farm level studies provide only a partial estimate of the costs of adaptation by excluding investments that need to be taken at the regional or country levels. Similarly, adaptation costs calculated by agricultural models are relatively low, unless they also include so-called ‘hard-infrastructure-measures’ such as the development and implementation of new irrigation techniques.

This section presents new estimates for adaptation costs related to agricultural R&D and irrigation efficiency improvement technologies in the OECD countries. The analysis is by no means an attempt to provide a full picture of adaptation costs for the agricultural sector, but it rather aims to provide an estimate of the orders of magnitude of potential expenditures needed to support adaptation measures. The purpose is also to complement the cost estimates provided by the World Bank in its 2009 study – Economics of Adaptation to Climate Change (EACC) – where the costs of adaptation in agriculture were calculated only for developing countries (Nelson et al., 2010). Based on the same methodology, this report presents the calculation of adaptation costs in agriculture for the OECD countries. The EACC study considered three types of measures: (1) R&D, (2) water infrastructure and (3) roads. As inland and coastal infrastructures in OECD countries are well developed, the present analysis only deals with calculating the costs of additional expenditures on (1) R&D and (2) implementation of more efficient irrigation equipment (see Annex 3 for more details).

Due to a lack of a widely accepted adaptation metric, the World Bank uses the number of malnourished children as a measure of adaptation level, or more specifically the level of investments in agriculture required to offset an additional increase in the number of malnourished children due to climate change. Because the number of malnourished children is much smaller in OECD countries, and is not expected to dramatically change under different climate assumptions, different benchmark measures are chosen. To estimate the cost of additional R&D, a 50% reduction of potential yield loss due to climate change (by 2050) is targeted, and for the estimation of irrigation efficiency improvements, it is assumed that countries strive for a 72% increase in irrigation efficiency by 2050.

The methodology to estimate additional R&D expenditures is based on a function with an estimated elasticity of changes in expenditures with respect to change in yields. First, a baseline of expenditures growth of both private and public R&D up to 2050 is established. Second, for a given scenario, a level of additional expenditures is calculated on the basis of a demanded change in yields. The methodology to calculate the irrigation efficiency improvement differs from the R&D measures. The adaptation expenditures are calculated as necessary investments in order to achieve the given minimum efficiency target for the OECD countries. First, an initial efficiency rate of the system is calculated on the basis of the share of each irrigation technology applied in respective OECD country. Second, a share of an inefficient irrigation system to be replaced is calculated, given a chosen level of irrigation efficiency. To the end the annualised costs of the potential irrigation system replacement are calculated. A detailed description of the methodology is provided in Annex 3.

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8. The costs calculated here do not reflect the exact costs of the measures presented in the modelling sections.

9. In case of the United States, the proposed adaptation measures offset about 50% of the potential yield losses of maize in Scenario 4. For this illustrational purpose, the overall R&D costs are calculated based on the assumption that they may offset 50% of potential yield losses also in other OECD countries.
Results of these computations show that the additional annual expenditures needed, through 2050, in agricultural R&D to reduce partly the potential yield decrease due to climate change for OECD countries amount to USD 2.3-4.5 billion for public R&D and to USD 3.0-5.3 billion for private R&D (total R&D equals USD 5.3-9.8 billion), depending on the scenario (Table 3). About 50% to 56% of additional agricultural R&D is expected to be carried out by the private sector, compared to current 45%. This suggests that reaching a target of 50% reduction of potential yield loss due to climate change would require substantial investment in R&D, creating large opportunities for the private sector.

The annual costs to reach the 72% target in improved irrigation efficiency over the different countries is projected to be USD 10.4 billion as shown in Table 3. The total investment costs for irrigation efficiency are higher than the costs in R&D investments, but as the effectiveness of these measures differ, one cannot conclusively derive which measure is more cost-effective. These estimations should not be seen as a precise cost figure but rather it sheds some light on potential costs when investing in specific technological measures to increase water efficiency in agriculture in OECD countries.

The total annual cost for implementing both measures amounts to USD 15.7-20.2 billion, depends on the scenario, as shown in Table 3.

<table>
<thead>
<tr>
<th>Cost Type</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total R&amp;D</strong></td>
<td>5.3</td>
<td>6.0</td>
<td>7.4</td>
<td>9.8</td>
</tr>
<tr>
<td><strong>Public R&amp;D</strong></td>
<td>2.3</td>
<td>3.0</td>
<td>3.2</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>Private R&amp;D</strong></td>
<td>3.0</td>
<td>3.0</td>
<td>4.2</td>
<td>5.3</td>
</tr>
<tr>
<td><strong>Irrigation efficiency</strong></td>
<td>10.4</td>
<td>10.4</td>
<td>10.4</td>
<td>10.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>15.7</td>
<td>16.4</td>
<td>17.8</td>
<td>20.2</td>
</tr>
</tbody>
</table>

Source: Own calculation.

There are only a few global studies that provide some estimates for adaptation in agriculture for developed countries (see Box 1 for more information). A few more estimates are available for developing countries. The cost estimates presented in Table 3 are relatively high in comparison to most of the estimates in the literature, although a direct comparison is fraught with difficulties as the effectiveness of the options varies across the studies.

Figure 17 shows selected regional estimates of the adaptation costs in agriculture. Although it is impossible to compare these estimates (due to different approaches, and different regional aggregation), and the low number of available studies do not allow for thorough analysis, some general observations can be drawn. The only study that provides an estimate for autonomous adaptation and accounts for transition costs, de Bruin (2013), suggests that the annual costs for autonomous adaptation may be as high as USD 35 billion in 2055 for developed countries, assuming an optimal level of adaptation. Another general finding is that all models indicate that adaptation costs increase with time. Not surprisingly, more severe climate change scenarios (or as in some models, the absence or low mitigation actions) require more adaptation investments to compensate for the larger negative effects of climate change.
Figure 17. Global estimates of adaptation costs in agriculture

Source: Own compilation.
Box 1. Review of existing estimates of regional costs of adaptation to climate change

**UNFCCC (2007)**

In 2007, UNFCCC estimated the costs of adaptation for six sectors including agriculture for 2030 (McCarl, 2007). The global cost of adaptation in agriculture is estimated at USD 7.8-8.9 billion, and for the high-income countries at USD 3.7-4.2 billion. This incorporates both public and private expenditures. The total costs of adaptation in agriculture is based on 1) costs of R&D including costs of extension and 2) physical capital expenditures both in terms of climate change and in terms of future evolutions in population and its food requirements (McCarl, 2007).

The assessment is based on historical trends and different climate scenarios. The business as usual (BAU) scenario assumes no climate change. Subsequently two climate change scenarios assume: i) no mitigation, (SRES A1) ii) some migration (SRES B1). For the first counter scenario the UNFCCC assumed 10% increase in research and extension funding and 2% in capital formation, while for the second one 8.6% and 0.4%, respectively.

**World Bank (2010)**

In 2010, the World Bank launched the Economics of Adaptation to Climate Change (EACC) study to provide up-to-date and consistent estimates of adaptation costs for developing countries (Narain et al., 2011). Based on the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model calculation, the World Bank (2010) reports USD 7.6-7.7 billion annually needed for agricultural adaptation measures in developing countries by 2050.

Two climate scenarios based on the A2 SRES scenario are used and compared to the business as usual scenario where current climate is assumed. One of the main indicators used in this study is the number of malnourished children. Climate change negatively affect food security and in both climate change scenarios number of undernourished children increases by 2050. The cost of adaptation is estimated by assuming that the level of public investment in agricultural sector can level the number of malnourished children to the level of business as usual scenario. Three types of public investments are considered in this paper; (i) agricultural research and development, (ii) irrigation efficiency and expansion, and (iii) rural roads.

**De Bruin (2013)**

None of the above estimates incorporate the costs of autonomous farm-level adaptation. De Bruin (2013) calculated the annual costs of adaptation in agriculture for both flow (autonomous) and stock (planned) adaptation until the end of this century. For developed countries stock and flow adaptation costs together amount to USD 68 billion, from which 34 billion is needed for autonomous adaptation and for developing USD 156 billion, from which 68 billion is needed for autonomous adaptation in 2055.

These estimates are based on the AD-RICE model, which treats adaptation as a policy variable. It calculates the effects of climate change on the economy by maximizing the regional utility function where in each period consumption and savings/investments are endogenously chosen subject to income and costs of climate change. Climate change costs include the residual damages, mitigation and adaptation costs (de Bruin et al., 2009; de Bruin and Dellink, 2011). Macroeconomic costs of adaptation efforts in agriculture are integrated within one ‘adaptation cost curve’.

For the agricultural sector the damage function is modified based on the crop yield variation information from the FARM model.

**IIASA (2007)**

Fischer et al. (2007) estimates the additional cost of irrigation water requirements caused by climate change from 1990 to 2080, using the Agro-ecological zoning (AEZ) model, developed by Food and Agriculture Organization (FAO) – International Institute for Applied Systems Analysis (IIASA). The global annual costs of additional irrigation cost were estimated at USD 24–27 billion by 2080, where the additional annual cost for developed countries are USD 8-10 billion, and for developing countries USD 16-17 billion by 2080. The climate mitigation action is expected to reduce the total cost to USD 16-17 billion; a reduction by USD 3-4 billion for developed and by USD 5-6 billion for developing countries. For the mitigated scenario the annual costs for increasing irrigation capacity for 2030 and 2050 are USD 8 billion, USD 12-14 billion, respectively.

In addition to the business as usual scenario, climate scenarios were constructed with different assumptions on mitigation actions: (i) no mitigation and (ii) partly mitigated scenario. For climate change projections, two GCM models were used (i) Hadley and (ii) CSIRO. The SRES A2 scenario was used as a proxy of unmitigated climate and SRES B1 of partly mitigated climate. Comparing the climate scenarios with the business as usual provides the estimates on future needs for irrigation.
8. Concluding remarks

This report describes the potential consequences of climate change on agriculture and discusses a set of possible adaptation measures to reduce some of the expected negative food security effects it may induce. Although the scenarios presented in this report offer only a stylised representation of possible future developments, several observations may be relevant for policy makers.

Adaptation can play an essential role in limiting some of the negative consequences of climate change (and stimulating positive impacts where applicable). Autonomous adaptation measures such as altering inputs to those that are more appropriate to new climate conditions, improving on-farm water retention in the soils or altering the timing of cropping activities are important to increase the resilience of food systems. These ‘good practices’ may, however, not sufficiently reduce future climate risks. Additional adaptation measures may thus be necessary to offset some of the remaining climate damages. This report shows in particular that developing improved seed varieties, transfer of technology and improving irrigation systems can make agriculture more resistant to changing climate conditions.

Access to new technologies can help in spreading more resistant varieties and improve global food availability. Additionally, the spill-over of productivity enhancing technologies for particular crops reduce their respective world prices and therefore increase food affordability although at a limited scale. The widespread adoption of technologies that are resistant to expected new climate conditions significantly reduces projected food prices in 2050 compared to the climate change baseline. Similarly, increasing the efficiency of irrigation systems or expanding irrigation infrastructures, where appropriate, can significantly reduce water stress and make farming practices more resilient to climate change.

The overall costs of adaptation are likely to be substantial if no mitigation actions are undertaken and current trends of emissions continue. These costs depend strongly on the targeted adaptation level, and the marginal costs always need to be evaluated against the marginal benefits they deliver. Due to the lack of common metrics for the effectiveness of adaptation, it is impossible to determine optimal adaptation strategies. Under the assumptions of this report, the estimates of potential additional costs in R&D and in improved irrigation technologies amount to USD 16-20 billion per year by 2050 for the OECD countries. These estimates are placed in the middle range of existing cost estimates for developed countries. Overall, the costs of adaptation tend to increase with time, when climate damages increase as well.

This analysis indicates that quantitative scenario analysis of adaptation to climate change is a very promising policy tool that can assist governments in comparing results of different policy paths.
REFERENCES


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OECD (2014b), “Status and characterisation of groundwater resources in agriculture in OECD countries”.


ANNEX 1. MODEL DESCRIPTION AND MODEL LIMITATIONS

To analyse the impact of climate change on agricultural production the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) is used. It has been developed at the International Food Policy Research Institute (IFPRI) and represents a combination of a partial equilibrium model and a hydrological model. The partial equilibrium agriculture model emphasizes policy and trade simulations, while the hydrological model simulates water systems and water stress. IMPACT is externally linked to specific biophysical crop models. This suite of models was developed to project global food supply and food security for the medium and long term (Rosegrant et al., 2012). Figure 18 presents the schematic overview of the IMPACT model.

Figure 18. Schematic model description

Source: Rosegrant et al. (2012).
In the partial equilibrium module of IMPACT, global agricultural commodity prices are determined annually at levels that clear international markets. Growth in crop production in each country is determined by crop and input prices, exogenous rates of productivity growth and area expansion, water availability, and crop modelled biophysical shocks due to climate change. The supply of crops and livestock is determined at the food production unit (defined as a specific watershed in a specific region, e.g. the Nile watershed in Egypt). Within each food production unit crop production is calculated separately for rainfed and irrigated areas, taking into account specific land and water conditions. Some countries, such as the United States, have several production units within their borders, while smaller countries are often aggregated within one production unit, e.g. Belgium and Luxembourg. The major drivers of agriculture supply are price levels of all crop and livestock commodities. Aggregate demand is a function of prices, GDP, and population and is comprised of five categories of commodity demand—household (food), livestock feed, intermediate demand (for processed goods), biofuel feedstock, and other uses. Food demand for agricultural commodities is determined by consumers’ responses to own- and relative price changes and their income level (Nelson et al., 2010; Rosegrant et al., 2012).

The water module of IMPACT computes the availability of water to irrigated farmland, after assessing the water demand for domestic (urban), industrial, environmental, and livestock sectors. This water availability for irrigated farmland is then used to calculate the yield shock due to water availability. To incorporate the biophysical processes, IMPACT is externally linked to 1) the Decision Support System for Agrotechnology Transfer (DSSAT) crop modelling suite (Jones et al., 2003), to simulate responses of five important crops to changing biophysical conditions (rice, wheat, maize, soybeans, and groundnuts), and 2) the Lund–Potsdam–Jena managed Land (LPJmL) model, to stimulate the responses of 11 arable crops (Bondeau et al., 2007).

Both biophysical crop models need detailed information on current and the future climate up to 2050. To simulate current climate conditions, the WorldClim data set (www.worldclim.org) is used, which is representative of 1950–2000 climate data and reports monthly average minimum and maximum temperatures and monthly average precipitation. To provide some idea of the uncertainties inherent in the climate change simulations, the climate results from two alternative general circulation models (GCMs) are used as alternative scenarios in the analysis. The first of these is a GCM developed at the Institute Pierre Simone Laplace (IPSL model) and the second one is the Hadley Centre Global Environmental Model (Hadley model) from the MET office in the UK (Johns et al., 2006). Both models are used to analyze future climate scenarios in preparation for the fifth Assessment Report of IPCC. They calculate the Representative Concentration Pathways (RCPs) taking into account a range of factors that determine future climate change (radiative forcing of greenhouse gases and land use change). For each RCP the information on emissions, concentrations and land use are provided (Van Vuuren, 2011a, b). Figure 19 presents emissions pathways for four representative concentration pathways and current emissions trend.
Both models show clear changes in precipitation patterns as compared to the “climate of the recent 50 years” (Figures 20 and 21). In general, high latitudes of the northern hemisphere are in both models expected to be wetter. More precipitation is also foreseen for Equatorial Africa and Asia. The IPSL model shows more distinctive changes, compared to the Hadley model. For instance, for some regions of Kenya, IPSL shows more than 100 mm increase in average precipitation per month, while the Hadley model estimates an increase of about 10 mm per month. Large differences are visible with regards to equatorial America. Where the IPSL model results show a significant increase in precipitation, the Hadley model calculates a large decrease in rainfall. For certain OECD countries e.g. Mexico, Poland and Germany the “direction” of change is inconclusive between these two models. Both models compute increasing trends in the average temperature, though with some regional differences.

Incorporating projections for crop yields from the crop models (DSSAT and LPJmL) and the water module, in the partial equilibrium economic framework of IMPACT, allows for assessing the combined effects of socio-economic and climate developments on agricultural production and future food availability.
Figure 20. Rainfall – changes in monthly average over whole year compared to reference – IPSL model RCP8.5

Source: DSSAT.

Figure 21. Rainfall – changes in monthly average over whole year compared to reference – Hadley model RCP8.5

Source: DSSAT.
Limitations to the model

IMPACT comprises a complex suite of modules. Each module has its strengths and limitations and imposes uncertainty on the numerical results. As in all models, IMPACT aims to be more detailed in those elements that are most central to the core of the topic for which it is intended, e.g. it accounts for crop-specific calories intake to determine food nutrition levels of children in developing countries, but is more stylised and aggregate in other domains. A number of limitations of the economic module of IMPACT need to be highlighted in the context of the present work.

Generally, all agricultural economic models feature simplified representations of the various agents’ behaviour and are based on past observations and current expertise. As a consequence, scenarios for the (long-term) future should be interpreted with caution and cannot be seen as forecasts. The realised effects of exogenous shocks, such as climate change, may turn out to be different from results given by these models. Furthermore, the exact behaviour of farmers, industries and consumers in the future is impossible to predict, and technological developments may occur differently from current expectations.

Second, like comparable agricultural economic models, e.g. Aglink, it does not have a fully specified production function for each crop; thus, the representation of the possibilities of farmers to switch between different production technologies is limited. Nonetheless, the major technologies are specified in the model in a crop- and region-specific manner. Clearly, a good representation of technology-switching is important with respect to adaptation to climate change.

Third, land use is only associated with crop production. No other land use types are incorporated in the model, limiting its ability to fully account for land use changes. The sensitivity of the land expansion parameters can be further tested, in order to best represent possible future land expansion. Note that, this module of IMPACT is currently being revised. It should be noted as well that more comprehensive land use modelling may be envisaged by the Secretariat using a soft-link to the OECD’s ENV-Linkages model, depending on the priorities set by EPOC for the next biennium.

Although the IMPACT water module is already complex, further improvements of the water components would help improve the representation of the impacts of climate change. Areas that would be valuable to explore is the role of weather volatility under climate change, as well as improving the integration of with crop models to improve the estimation of water stress. More nuanced linkages with livestock and other sectors demand for water would also allow for improved modelling of total water demand.

The economic module of IMPACT relies heavily on data input from the crop models DSSAT and LPJmL, when calculating the overall effects of climate change on agricultural yields. These inputs determine to a large extent the behaviour of crops under changing climate conditions. Müller and Robertson (2014) discuss differences and limitations of using these two crop models to provide inputs to agriculture models, including IMPACT. These models however only consider direct abiotic stresses to the plant. This means that important abiotic stresses such as weeds, pests, and diseases which may change significantly with climate change are not accounted for.

The representation of climate change impacts is also stylised. For instance, all climate variables are assumed to change linearly between their values in 2000 and 2050. This assumption eliminates climate variability events such as droughts or high rainfall periods and also assumes that the forcing effects of GHG emissions proceed linearly. This may underestimate the benefits of risk-reducing technologies such as irrigation efficiency and drought tolerance. It is also important to note the average of running the model with all of the variation is unlikely to equal running the model on an “average” weather. Figure 22
illustrates the differences between variable monthly precipitation in Spain from IMPACT, and using the average weather assumption.

Figure 22. Comparing variable and average weather in Spain (IMPACT)

Additionally, it should be noted that the GCM do not model some other aspects of climate change such as sea level rise that might be significant for assessing climate change impacts on agriculture located in coastal areas. The effect of this assumption may on the one hand be an underestimation of the effects from climate change. On the other hand, climate effects in the shorter run are likely to be overestimated.

This has consequences for the projections of adaptation. First, autonomous adjustment processes are assumed to be possible in a gradual manner and variability is ignored. The absence of such variability in climate impacts would, ceteris paribus, suggest that the ability to adapt is overestimated in the model, and actual transition costs may be larger than depicted. Second, the overestimation of short-term impacts may imply that there is more time to adapt to emerging impacts than suggested by the model and thus transition costs may be overestimated, at least in the short run.
ANNEX 2. DESCRIPTION OF THE WATER MANAGEMENT SCENARIOS

Irrigation efficiency improvement

Some irrigation systems are inefficient in terms of how much water actually reach the plant compared to how much water is taken from a source (river or reservoir). For instance, the efficiency of surface irrigation (flooding irrigation) is on average about 60% in the OECD countries, what means that about 40% of water is lost during the transportation to the field. Sprinklers irrigation, when water is delivered or rather sprayed on crops via a pressurised system, increase the water efficiency to about 75%. The most efficient irrigation system, so called drip irrigation, delivers water directly in the neighbourhood of the roots of a plant via a dropping pattern. Such system increases the efficiency in water use to about 90%. Changing irrigation technology towards a more efficient one or improvement of low efficient irrigation technology by means of, for instance, insulating canals or covering canals to reduce evapotranspiration is a good way to prevent water loss.

Figure 23 presents the average irrigation efficiency of each OECD country. The highest efficiency in irrigation water use is achieved in Israel – about 86%, the lowest efficiency are found in Chile, Mexico and Turkey – about 61%. The efficiency level is strongly related to the predominant type of irrigation system used in a country. In Israel, almost three quarters of total irrigated land is equipped with high efficient drip irrigation. Mexico and Chile are predominantly equipped with surface irrigation.

![Irrigation efficiency and share of irrigation technologies in the OECD countries](source)

Source: Own compilation.

The use of efficient water technologies contribute to an increase in farm production and improved physical water productivity. Overall the OECD average water application rate per irrigated hectare decreased by 7% between 1990-92 and 2002-04, while in most cases the volume of agricultural production increased (OECD, 2010b).
The demand for water by agriculture across OECD countries is almost constant; however, due to growing demand from other sectors, the pressure on water resources in some regions increases (OECD, 2013). This may induce a water stress. Some states of the United States, e.g. California, and many Mediterranean countries battle already with increasing water stress (OECD, 2010b). Figure 24 provides more detail on the water stress level in a selection of OECD countries. Although, in itself, water stress may impose negative consequences on productivity, with a supporting set of policies it may stimulate policies targeting more efficient water allocation and adoption of sustainable water management techniques. However, according to OECD (2010) in many countries farmers are only covering the operation and maintenance part of the water supply costs, with little recovery of the capital costs for water supply infrastructure. Therefore it is important to ensure that charges for water supplied to agriculture reflect full supply costs.

Figure 24. The extent of water stress and cost recovery for surface water delivered to farms across OECD countries late 2000's

Notes:
1: Water stress:
Water stress defined as water withdrawals by all users (i.e urban, industrial, power and agriculture) a percentage share of annual water availability (i.e quantity of water from precipitation net of evapotranspiration and inflowing rivers from neighbouring countries). OECD uses the following thresholds for water stress: Low - below 10%; Moderate -10% - 20% range; Medium - above 20%; Severe - above 40%.

2: Cost recovery:
A: Less than 100% cost recovery of Operation and Maintenance Costs, with Capital Costs supported
B: Less than 100% cost recovery of Operation and Maintenance Costs and Capital Costs
C: 100% cost recovery of Operation and Maintenance Costs but less than 100% recovery of Capital Costs
D: 100% cost recovery of Operation and Maintenance and Capital Costs

Source: calculations based on AEI.

Theoretically, the implementation of water efficient technologies contributes to water stress reduction, and in general, to more sustainable resource use. In practice, however, in some places water savings technology increase water demand. In Pakistan, farmers who use efficient water technologies actually use the ‘saved’ water to intensify agricultural production and expand the irrigation area (Ahmad et al. 2013). Similar situation happened in Kansas, United States. According to Pfeiffer and Lin (2013), the intended reduction in water use by using more efficient irrigation technologies did not occur due to shifting cropping patterns towards high-value water-intensive crops. In order to maintain the effect of decreasing
water stress, measures that support more efficient water use should be complemented with appropriate regulations and policies to limit the use of ‘saved’ water (Ahmad et al. 2013).

Another, unintended effect of using very efficient irrigation technologies is a reduction in ground water replenishing. The inefficient water systems on one hand ‘waste’ water in terms of delivering less water to the plant, on the other hand these systems also fill the groundwater reservoirs and therefore contribute to a greater supply of ground water. OECD (2014b) discussed this effect in detail.

**Irrigation expansion**

Irrigation is often seen as a mean to increase agricultural yields and enhance the quality of crops. It is often described as self-insurance tool against drought and is used to smooth farmer’s income (Amigues et al., 2006; Foudi and Erdlenburch, 2011). Globally around 360 million hectares is irrigated. Future irrigated water availability will strongly depend on current and future precipitation, but also on future socio-economic developments that will determine water demand for other sectors of the economy and final consumers. According to OECD (2013) major new irrigation infrastructure development will be limited due to financial and physical limits. Figure 25 shows that many studies that are considering (growing) water demand from other sectors assume that global irrigated areas are stable or slightly increasing. Most of the time the increase is associated to irrigated areas in developing countries.

![Figure 25. Projected global irrigated area](source.png)


According to the OECD Environmental Outlook 2050, total water supply in the OECD countries may decrease by 2050 compared to 2000 level with the strongest decrease of water availability for agricultural sector. It is assumed that total irrigated area remains constant but irrigation efficiency increases significantly. Total demand for water in the rest of the world is expected to increase significantly. By 2050 agriculture may be still one of the major users of water, but the demand from other sectors such as electricity and manufacturing may increase a few folds. Under the Business as Usual scenario, total
demand for water increases by 55%. Additionally, the quality of available water sources is expected to worsen posing additional difficulties in obtaining sufficient amount of drinking water. Based on recent observation (OECD, 2013) changes in irrigated area were positive in 1990s, however in recent years a decrease in irrigated areas in OECD countries was observed.

At the farm level, the empirical literature shows that farmers are sensitive to past mean and variance of climate and build the expectations of future events based on past trends (Foudi and Erdlenbruch, 2011; Bozzola and Swanson, 2014; Di Falco and Veronesi, 2013). Not surprisingly, farmers are also sensitive to variability of their income. Farmers with relatively stable income are less inclined to invest in irrigation (Koundouri et al., 2009 and Foudi and Erdlenburch, 2011). This affects the degree to which farmers will adopt available technologies to maximize and smooth own profits. Irrigation requires significant up-front investments and may be relatively labour intensive. Decision on whether or not to invest in irrigation will therefore depend on socio-economic developments, future water availability and current and future agri-environmental policies.
ANNEX 3. METHODOLOGY TO CALCULATE ADAPTATION COSTS

Methodology to calculate R&D adaptation costs

In order to estimate the additional annual cost in agricultural research and development (R&D) due to climate change in OECD countries, the World Bank methodology was applied (Nelson et al., 2010). Since this methodology was targeting developing countries, some modifications were necessary. The same method was applied to estimate the adaptation costs in public and private sectors. It is important to include the private R&D since there have been a slowdown in the growth rate of public agricultural R&D investments and an increase rate of the private R&D (Pardey et al., 2009).

The database that was used for this analysis was prepared based on the OECD Science, Technology and R&D Statistics database. To calculate future expenditures for public agricultural R&D the “Government budget appropriations or outlays for RD” in agriculture was used. For the private expenditures estimation the “Gross domestic expenditure on R-D by sector of performance and socio-economic objective in NABS2007” was used. The private Agricultural R&D expenditure is defined as some of private NPOs and business enterprise R&D expenditures. To estimate private expenditures of agricultural R&D in the USA, data from Fuglie et al. (2011) “Research Investments and Market Structure in the Food Processing, Agricultural Input, and Biofuel Industries World Wide (pp. 9, Table 1.5)” was used and converted into 2005 US$ using the GDP deflator from the World Development Indicators. Some missing values for the expenditures were estimated using the latest available data and the historical growth rate of investment in the particular country or where only one estimate was provided, the growth rates for the OECD were used. Additionally, where no information were provided for the private sector R&D expenditures the R&D expenditure ratio of private to public expenditures between 2001 and 2010 (i.e. 0.554) was used.

First, following the World Bank (2010) methodology, the baseline R&D expenditures in 2050 without climate change impacts based on equation (1) were estimated.

\[
AR_n = \left[ \left( \frac{g_n g_a}{10000} + 1 \right) AR_{n-1} \right]
\]

where ARn – is the annual expenditures on agricultural R&D 2011-2050, and \( g_a \), is the multiplier of historic growth in Table 4. \( g_n \), represents the historical growth rates by countries.

11. The R&D data for Chile and Turkey are unavailable; therefore, these two countries are omitted in our R&D cost estimation.
13. Available at http://stats.oecd.org/Index.aspx?DataSetCode=GBAORD_NABS2007: Accessed on 5 March 2013. Note that this dataset includes R&D expenditure by government and higher education, which are seems to be suitable data to use as public R&D expenditure. However, the data contains largely much of missing values compared with aforementioned dataset.
Table 4. Assumed multipliers of historic growth rates (ga) of agricultural R&D

<table>
<thead>
<tr>
<th>Agricultural R&amp;D</th>
<th>2011-2020</th>
<th>2021-2030</th>
<th>2031-2040</th>
<th>2040-2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>ga (%)</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>


The additional agricultural adaptation cost in R&D by 2050 ($AR_{\text{scenario}}$), both private and public, were calculated as follows:

$$AR_{\text{scenario}} = \left[ -0.5 \left( \frac{Yield_{\text{scenario}} - Yield_{\text{baseline}}}{Yield_{\text{baseline}} \cdot \epsilon_{\text{Research}}} \right) \right] AR_{\text{baseline}}$$

(2)

where $Yield_{2050}$ being the average of cereal yields in each sectors, and $\left( \epsilon_{\text{Research}} \right)$ is the yield elasticity with respect to R&D expenditures vary by regions to regions (Table 5).

Table 5. The yield elasticity with respect to R&D expenditures

<table>
<thead>
<tr>
<th>Regions</th>
<th>Elasticity</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan and Korea</td>
<td>0.14</td>
<td>Pratt &amp; Fan (2010)</td>
</tr>
<tr>
<td>United States, Canada, and Israel</td>
<td>0.187</td>
<td>Alston (2010)</td>
</tr>
<tr>
<td>Europe</td>
<td>0.22</td>
<td>Barnes (2002), Thirtle et al. (2008)</td>
</tr>
<tr>
<td>Australia and New Zealand</td>
<td>0.22</td>
<td>Mullen (2007)</td>
</tr>
<tr>
<td>Mexico</td>
<td>0.296</td>
<td>World Bank (2010)</td>
</tr>
</tbody>
</table>

Source: compiled by Authors.

It should be noted that elasticises used in this analysis are different from those of World Bank. The elasticities used in this study are lower because developed countries have been redirected away from farm productivity toward other concerns, such as the environmental effects of agriculture; food safety and other aspects of food quality; and the medical, energy, and industrial uses of agricultural commodities (Pardey et al., 2009). As a consequence, the additional cost will be larger in OECD countries even if the impact of the climate changes is the same.

Methodology to calculate irrigation investment costs

The World Bank methodology is applied for the estimation of the annual cost for the investment in irrigation efficiency technologies in OECD countries (Nelson et al., 2010). First an initial basin efficiency rate ($BE_0$) is calculated on the basis of the share of each irrigation technology applied in respective OECD country (see Figure 23).

The concept of basin efficiency describes irrigation water-use efficiency at the river-basin scale and is defined as the ratio between total irrigation water consumption (TC) and beneficial irrigation water consumption (BC):

$$BE_1 = \frac{BC}{TC}$$

(1)
Where subscript “0” denotes the base scenario and “1” denote the alternate irrigation investment scenario. The total irrigation water consumption is calculated using the share of total irrigated area in 2050 with the more efficient irrigation technology (X) namely sprinkler or drip technology:

\[ TC_1 = BC_0 \cdot \frac{1 - X}{BE_0} + BC_0 \cdot \frac{X}{E_i} \]  

Combining (1) and (2) and simplifying results give:

\[ X = \frac{(BE_0 / BE_1) - 1}{(BE_0 / E_i) - 1} \]  

The irrigation efficiency investment costs (IE invt) consist of three components. First is the cost related to the change to the more efficient irrigation efficiency per hectare (IE cost). The second component is the total irrigated area (AI) in hectare in 2050. Last, the share of total irrigated area in 2050 with the more efficient irrigation technology. This together will give the total investment costs for a country:

\[ IE_{invt} = IE \cdot cost \cdot AI \cdot X \]  

The investment cost are only relevant when BE1 is higher than BE0, if this is not the case, the costs are not calculated. The target for a minimum efficiency rate is set on 72% and this can be reached by increasing the share of sprinkler or drip technology. Following the World Bank methodology, one third of the total costs are used to account for the investment costs associated with increasing irrigation efficiency.

**Data description, sources and assumptions**

The efficiency rate of surface, sprinkler and drip technology is 60%, 75% and 90%, respectively (FAOSTAT). The two exceptions are: Portugal with an efficiency rate of 80% for drip irrigation (www.iwra.org/congress/2008/resource/authors/abs878_article.pdf) and Spain with 58% for surface, 75% for sprinkler and 96% for drip irrigation (http://ec.europa.eu/environment/agriculture/pdf/irrigation.pdf).

The basin efficiency target is set to 72% for all countries with the exception of Japan. The agricultural sector of Japan consists mainly of rice production where sprinkler or drip technologies are not applicable. To increase the irrigation efficiency in Japan, different management technologies may be used including more precise timing of the irrigation process. This is incorporated by setting BE1 to 65% which means a 3% increase of irrigation efficiency for Japan.

For the total irrigated area in 2050 in hectare, the average of the available years between 2005 and 2010 is taken using OECD data (www.oecd.org/agriculture/sustainable-agriculture/agri-environmentalindicators.htm) for most of the countries. For Belgium, Denmark, Finland, Luxembourg, Netherlands and Sweden, data on the total irrigated area in 2005 is collected from FAOSTAT. Data for Iceland is not available.
### The cost of the irrigation technology per hectare

<table>
<thead>
<tr>
<th>Country</th>
<th>Costs of the technologies</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>European countries</strong></td>
<td>USD 1 700 for surface USD 2800 for sprinkler USD 3 950 for drip</td>
<td>FAOSTAT [ftp://ftp.fao.org/docrep/fao/010/a1336e/a1336e.pdf]</td>
</tr>
<tr>
<td><strong>Australia and New Zealand</strong></td>
<td>USD 2 274 for sprinkler USD 5000 for drip</td>
<td><a href="http://www.nwc.gov.au/__data/assets/pdf_file/0013/10921/Waterlines_53_PDF_Fellowship_-_Technological_change_in_the_irrigation_industry.pdf">www.nwc.gov.au/__data/assets/pdf_file/0013/10921/Waterlines_53_PDF_Fellowship_-_Technological_change_in_the_irrigation_industry.pdf</a></td>
</tr>
<tr>
<td><strong>Poland</strong></td>
<td>USD 1 649 for sprinkler USD 3 950 for drip</td>
<td><a href="http://www.infraeco.pl/pl/art/a_15605.htm?plik=637">www.infraeco.pl/pl/art/a_15605.htm?plik=637</a></td>
</tr>
<tr>
<td><strong>Chile, Korea, Japan and Mexico</strong></td>
<td>USD 2 730 for sprinkler USD 3 927 for drip</td>
<td>Data not available, the average costs of the other OECD countries is used</td>
</tr>
</tbody>
</table>

### Share of technology used

<table>
<thead>
<tr>
<th>Country</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Austria, Belgium, Denmark, Netherlands, Norway</strong></td>
<td>Eurostat <a href="http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do;jsessionid=9ea7d07e30d67044a33a8f1b4d088258bb0df1bedb2d.e34MbxeSahmMa40LbNiMbxAMbNqOeO">http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do;jsessionid=9ea7d07e30d67044a33a8f1b4d088258bb0df1bedb2d.e34MbxeSahmMa40LbNiMbxAMbNqOeO</a></td>
</tr>
<tr>
<td><strong>Canada, Finland, France, Japan, Korea, Mexico, New Zealand, Switzerland, Turkey, United Kingdom</strong></td>
<td>FAO <a href="http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=f">www.fao.org/nr/water/aquastat/data/query/index.html?lang=f</a></td>
</tr>
<tr>
<td><strong>Chile, Czech Republic, Estonia, Germany, Hungary, Israel, Italy, Poland, Slovak Republic, Spain</strong></td>
<td>ICID <a href="http://www.icid.org/annualreport.html">www.icid.org/annualreport.html</a></td>
</tr>
<tr>
<td><strong>Portugal</strong></td>
<td>National Statistical Institute – 2009 Agricultural Census</td>
</tr>
<tr>
<td><strong>United States</strong></td>
<td>USDA <a href="http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/fris08_1_04.pdf">www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/fris08_1_04.pdf</a></td>
</tr>
<tr>
<td><strong>Iceland</strong></td>
<td>Data not available</td>
</tr>
</tbody>
</table>