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Modelling Adaptation to Climate Change in Agriculture

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The publication of this document has been authorised by Ken Ash, Director of the Trade and Agriculture Directorate.

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Abstract

Modelling Adaptation to Climate Change in Agriculture

by

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This paper investigates how climate change can affect agricultural production and proposes some adaptation measures that could be undertaken to mitigate the negative effects of climate change while enhancing the positive ones. The paper stresses the importance of planned adaptation measures and highlights possible strategies for reducing risk and improving resilience. To quantify the possible effects of climate change and the effects of adaptation measures this study uses the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). The analysis first explores the potential effects of climate change on yields and prices. It then goes on to analyse the potential impacts of two distinctive sets of adaptation strategies on yields, prices, and food security, namely: *i)* research and development (to develop new crop varieties that are better suited to changed climate conditions) and *ii)* changes in irrigation technology. Last, the analysis in this paper estimates the public and private investment needs in research and development (R&D) for developing new crop varieties, and further develops estimates of the cost of improving irrigation technologies in OECD countries.

The OECD Secretariat would like to thank the International Food Policy Research Institute (IFPRI) for providing OECD with access to the IMPACT model. The inputs and comments received from IFPRI colleagues, in particular Sherman Robinson and Keith Wiebe, are much appreciated.

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Keywords: long term agricultural scenarios, climate change, adaptation to climate change, modelling adaptation, costs of adaptation.

JEL Classification: Q18, Q54, Q58

Table of contents

Tables

Figures

Executive summary

Issues at stake

For centuries, the global food system has been evolving and adapting to changes, keeping pace with growing demand for food and fibre. However, a key concern is whether the agricultural sector will be able to continue to produce enough food at affordable prices as the world's population approaches 9 billion people, particularly if climate change and water shortages hamper global agricultural production.

The impact of climate change on food prices will depend on the direction and magnitude of climate change, and on the agricultural sector's adaptive capacity, the latter being affected by the chosen adaptation strategies. Adaptation strategies, such as introducing new plant varieties that are better adapted to new climatic conditions, or implementing strategies to ensure that water can be delivered to crops in regions increasingly exposed to drought, may offset some of the negative impacts of climate change and provide additional benefits.

Methodology

This paper investigates how long-term scenarios for agricultural production can be affected by climate change. It projects yields, food availability and prices, and changes in land use under certain climate conditions. These long-term projections are then used to assess the effectiveness and costs of selected adaptation strategies.

The aim of this study is threefold: *i)* to analyse how climate change may affect agricultural yields, *ii)* propose adaptation strategies and measures to reduce the negative effects of climate change on agriculture and *iii)* provide some estimates of the magnitude of these adaptation costs for OECD countries. In addition, model-based scenario analysis can project the effects of climate change on agricultural prices, consumption patterns, trade and land use. This study uses the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). Unlike most other agri-economic models, IMPACT models the interactions between global food supply and demand, trade, income growth and population growth, and combines this with a water basin management model.

This report presents estimates of the public and private investment in research and development (R&D) necessary to develop new crop varieties, as well as estimates of the cost of improving irrigation technologies in OECD countries. Some adaptation actions may be costly to implement. However, very few estimates of adaptation costs have been produced, which makes this study's contribution to the literature particularly valuable. The approach used to assess adaptation costs in this study is based on a methodology developed by the World Bank (2010).

Main results

The results from the IMPACT model simulations imply that by the middle of the 21st century, the prices of agricultural commodities will be higher than current levels as a result of increased demand for food driven by population and income growth, diets that are richer in protein, and increased demand for biofuels from the energy sector. This is before taking into account any negative effects caused by climate change. Increased competition for land from human settlements and industry, and for conservation purposes, may limit the opportunity to increase the area for agriculture. Despite continuing increases in agricultural productivity, by 2050 the real prices of rice and wheat could increase by about 25% from 2005 prices; the real price of maize, an important food and feed crop, could increase by 50%.

The study's results show that the impacts of climate change may negatively affect the growth rates of yields for most commodities in most countries. Climate change effects may offset some of the positive effects of technological growth; however, nominal yields are still expected to be higher than today. For instance, global yields of maize, wheat and rice are projected to decline by 10%, 7% and 6%, respectively on average in the OECD countries, as compared to a situation where the current climate conditions would prevail. In some regions, the results show that climate change could reduce yields of certain crops by as much as 25%, as in the case of maize in North America or wheat in Australia. As a result of climate change, the real prices of all agricultural commodities would increase, with the prices of maize, rice and wheat projected to increase by up to 30% in the most extreme climate scenario.

Climate change is likely to affect the poorest populations most, and to increase food insecurity in many regions. In particular, compared to a situation without climate change, the number of malnourished children in sub-Saharan Africa would be expected to increase as the severity of climate change increases. Other regions in Asia and North Africa are also sensitive to progressive climate change.

This study analyses how adaptation measures can limit some of the consequences of climate change (and can produce net benefits in some cases). Autonomous adaptation measures by producers, such as improving on-farm water retention in soils or altering the timing of cropping activities, play an important role in increasing the resilience of food production systems. Although it is crucial that such strategies continue to be implemented, they may not be sufficient to offset the effects of climate change. Additional "planned" adaptation measures may also be necessary. Among these measures, this study assessed the impact of two: *i)* research and development (to develop new crop varieties that are better adapted to changed conditions) and *ii)* irrigation technology (improving irrigation efficiency and extending irrigation systems).

Extreme climate events such as droughts or heat waves are likely to occur more frequently. Developing new crop varieties that are drought resistant and better adapted to higher temperatures would help to maintain yields in these conditions. This study finds that adopting such varieties in the United States could reduce world prices of maize and wheat in 2050 by 3% and 1%, respectively, compared to the situation with climate change but without such varieties adoption; if these varieties were adopted in all OECD countries, world prices of maize and wheat could decrease by 4% and 2%, respectively. Livestock prices could decline as a result of lower prices for feed. Increased productivity in maize and wheat would also decrease pressure on land.

By 2050, this study projects that demand for land and water for agricultural use will increase globally, more so with climate change. Improving irrigation systems would offset some of this demand. In particular, pressurised irrigation systems (sprinklers and drip irrigation) decrease water demand by the agricultural sector and increase the efficiency of water use. As such, these systems decrease climate risks in general and may prevent large yield losses during droughts on land where these systems are installed.

Unless regulatory mechanisms are in place to govern the use of water “saved” by efficiency measures, farmers often use the additional water to increase food production by expanding irrigated land or by converting to higher-value, higher-profit commodities. Investment in more efficient irrigation systems may otherwise also benefit other sectors in the economy when the “saved”’ water is directed out of the agricultural sector. Or it may be used to increase the lifetime of aquifers. In all of the projected scenarios, improved water efficiency contributes to lower agricultural prices. Under the irrigation management scenarios used in this study, prices for maize, rice, potatoes, and vegetables fell by between 1.5% and 3% compared to a situation with climate change but without improved irrigation management.

Trade may help offset the economic consequences of the most harmful impacts of future extreme climatic events. Because climate impacts differ regionally, investments in local and international transport 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.

If actions to mitigate climate change are not sufficient and greenhouse gas emissions continue to increase, the overall costs to adapt to changed climate conditions are likely to be substantial. Moreover, adaptation costs will likely increase with time. However, because there is no common measure of adaptation with which to evaluate the cost-effectiveness of specific adaptation measures, it is difficult to determine optimal adaptation strategies.

The results of this study suggest that annual adaptation costs in agricultural research and development and in improved irrigation technology together could amount to between USD 16 and 20 billion by 2050 for OECD countries. These estimates fall in the middle of the range of existing cost estimates for developed countries. Some of these costs may be borne 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 spending will be larger than public R&D spending.

1. Introduction

For centuries, the global food system has been evolving and adapting to change. However, agricultural sector is confronted with growing constraints on its ability to supply adequate and affordable quantities of food (Tilman et al., 2011; OECD/FAO, 2012) as the result of an increasing global population, changing diets, and growing demands for non-agricultural land use. Moreover, ongoing soil degradation, water depletion and the decreasing capability of ecosystems to sustain their functions increase the challenge of maintaining adequate food production. Climate change is already putting additional pressure on agricultural production and its effects are expected to become more important in the future (Lobell et al., 2011; Foley et al., 2011; Foresight, 2011).

Assuming that current policies continue, average yields are projected to fall by between 5% and 20% by 2050, depending on the severity of climate change (Cline, 2007; Parry et al., 2007; Nelson et al, 2014; IPCC, 2014), with the largest decrease in productivity occurring in the least developed countries. Climate change can, however, also generate benefits for some agricultural sectors in certain regions. For instance, some countries may gain from longer vegetation periods and the possibility of growing more profitable crops. Moreover, yields of various crops may be increased through the CO_2 fertilisation effect, although this is highly debated (Challinor et al., 2009; Peltonen-Sainio, 2012). Scenario analysis can highlight the importance of these interactions.

This paper investigates long-term scenarios for agricultural production and how future production could be affected by the effects of climate change. It focuses on projections for yields, food availability and prices, and changes in land use. These long-term projections are then used to assess the potential mitigating effects of climate change adaptation. The aim of the study is threefold: *i)* to analyse the potential impacts of climate change on the agricultural sector; *ii)* to propose adaptation strategies and measures to reduce the negative impact that climate change might impose on the agricultural sector; and *iii)* to provide some estimates of the cost of adaptation for OECD countries.

This work builds on two previous OECD reports: Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments (OECD, 2008) and Climate Change and Agriculture: Impacts, Adaptation and Mitigation (OECD, 2010a). Both of these reports underline the importance of building adaptive capacity to reduce the negative impacts of actual or expected climate change. OECD (2008) estimates the effects of climate change in different sectors without focussing specifically on agriculture; OECD (2010a) focuses mainly on agriculture but does not provide quantitative information about either the effects of climate change or of adaptation efforts.

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

This study uses the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), developed by the International Food Policy Research Institute (IFPRI), to model climate change scenarios because this model has a comparative advantage in representing the climate- and water-related aspects in agricultural production over other agri-economic models.[1] This study analyses global agricultural production along with detailed regional disaggregations. Explicit attention is given to OECD countries where possible.

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

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[1] The IMPACT yield projections were chosen as the central projection for the Agricultural Model Intercomparison and Improvement Project (AgMIP) project.

2. Global food availability in the long-term scenarios

Several factors shape the future of the agricultural sector. The demand for food depends on, among other factors, population growth, diet composition and income levels. The supply of agricultural goods is, to a large extent, determined by the 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 20th 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 owing to a variety of factors, including major droughts, bioenergy policies and price increases for agricultural inputs. The *OECD-FAO Agricultural Outlook 2013* projects that prices for crops and livestock will remain at high levels for the next decade (OECD/FAO, 2013). The prices of grains are expected to remain near their 2013 levels, but the prices of oil seeds may increase towards 2020 owing to increased demand in the food and energy sectors. As a result of increasing demand for meat, the price of livestock will also be pushed upwards. Short- and medium-term projections such as these depend strongly on economic and policy developments, whereas long-term scenarios for agricultural production focus more on underlying trends, not least those related to natural resources and possible climate constraints.

There is by no means a consensus regarding how agricultural prices may develop by the period 2030-50. Some studies project further decreases in crop prices; others project possible sharp price increases. Von Lampe et al. (2014) compared the price projections for agricultural commodities produced by several agricultural models using a common set of assumptions. Six out of the ten models used in this study projected a price increase for agricultural commodities, one model showed practically no price change, and three models projected a decrease in 2050 prices compared to those in 2005. The aggregate price index of agricultural commodities is projected to change between -15% and +37% compared to 2005 when using "business as usual" economic and population trends (von Lampe et al., 2014; see below for more on this *Reference* scenario).

This section considers possible scenarios for agricultural markets in 2050, giving explicit attention to potential consequences for food availability of climate change in OECD countries. The IMPACT model is used to analyse agricultural markets in the future and the impact of climate change on agricultural production. IMPACT incorporates data from biophysical crop models, as well as supply, demand and trade data, in its projections. Moreover, it incorporates data from a hydrological model to account for changes in water availability (Rosegrant et al., 2012). A description of the IMPACT model, its schematic overview and a discussion of some of its limitations can be found in Annex A.

Acknowledging that there are many uncertainties concerning potential socio-economic developments and changes in climate patterns in the future, focussing on only one scenario would be misleading. Therefore, to shed light on the range of possible scenarios, two different sets of "climate conditions" are modelled: one reflects current climate conditions; the second reflects consequences induced by continued high levels of greenhouse gas (GHG) emissions. To reduce climate modelling bias such as differences in projected temperature and precipitation changes, the results from two different climate models are considered. Another important set of inputs for agri-economic modelling concerns the assumptions that are made about crop responses to changes in precipitation and temperature. Using the same set of climate parameters, different crop models may project different crop responses as a result of the assumptions that each model makes about agricultural production processes. This study uses input from two different crop models. The results produced by different combinations of climate and crop models may, therefore, present a plausible range of possible future scenarios.

Throughout this report, a set of economic indicators is used to highlight future developments in agricultural markets. These indicators include the world prices of various agricultural commodities, average crop yields and land allocations. The number of available calories per capita and the number of malnourished children (a child is defined as between the ages of 0 and 5 years old) are used as a proxy for food security. Where appropriate, trade patterns are also discussed. The world price level of agricultural commodities, one of the primary economic indicators in this study, reflects the changes on the international market and largely drives changes in trade patterns in the IMPACT model.[2] Crop yields and changes in land use indicate the responses by farmers to changing biophysical conditions and to price levels.

For purely illustrative purposes, modelling results are presented for the four aggregate regions that cover all OECD countries. They are: *i)* Australia, New Zealand and Chile; *ii)* Korea and Japan; *ii)* North America; and *iv)* OECD-Europe. To provide context regarding developments in the agricultural market in other parts of the world, and to analyse potential food security issues, the results for four regions that represent low-income countries and are particularly vulnerable to food insecurity are also presented. They are: sub-Saharan Africa, Middle East and North Africa (MENA), South Asia, and Southeast 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 on, among other issues, simulations of future climate change conditions (von Lampe et al., 2014). Several modelling groups with different crop, agricultural and economic specifications participate in AgMIP to compare their results. The insights gained from AgMIP substantially improve the information available about the effects of climate change on agriculture. There are two main advantages in using AgMIP scenarios. First, they have been peer-reviewed. Second, when possible, additional context about the effects of climate change on agriculture is provided based on the results produced in other models that used the same assumptions about socio-economic and climate variables.

To analyse the impact of climate change on agriculture, two crucial sources of information are needed: 1) assumptions about socio-economic factors such as population and economic growth, which are essential to specify demand-side developments; and 2) information on future climate conditions, needed to assess changes in future yields and therefore changes on the supply side. In addition, a reference scenario is needed against which the different modelling results can be compared to assess the magnitude of change. As the basis for this set of analyses, newly developed standardised scenarios – prepared for the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) – are used in this study. Table 1 presents a brief overview of the scenarios and their assumptions.

The **socio-economic assumptions** are based on the so-called Shared Socio-economic Pathways (SSPs). These include assumptions about population and GDP growth by country to the year 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* scenario, global population reaches just above 9 billion people by 2050. The majority of the population growth

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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

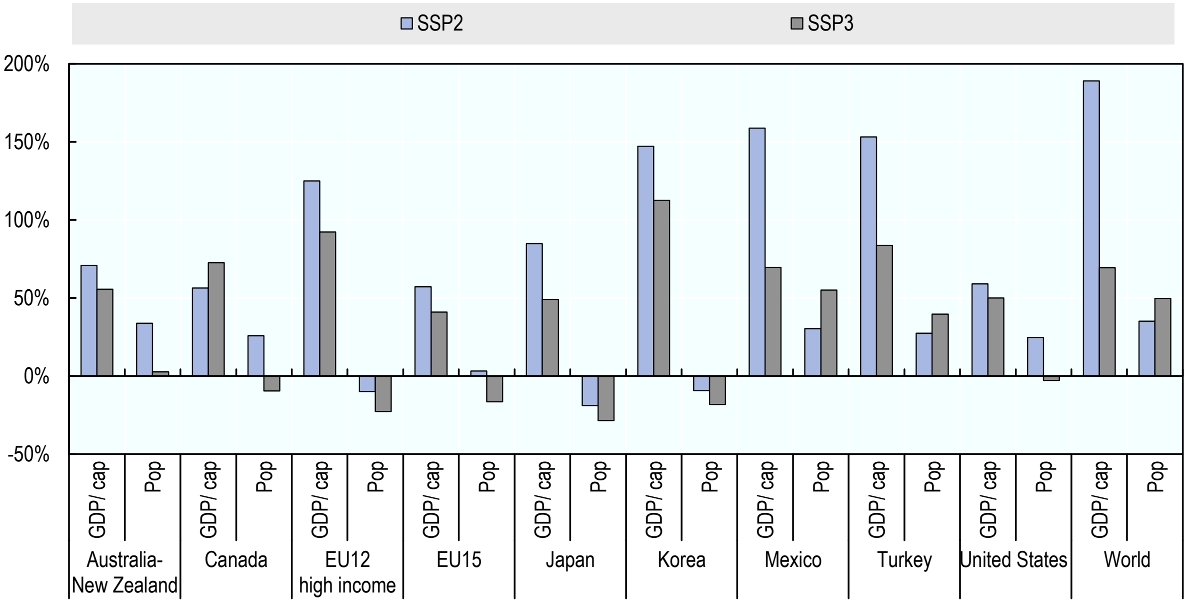
is expected to take place in non-OECD countries. The combined group of OECD countries is also projected to have a larger population compared to 2010, except in a few EU countries, as well as in Japan and Korea, where populations are forecast to fall. Overall, GDP in OECD countries is expected to almost double, and global GDP is expected to increase two-and-a-half times between 2010 and 2050. There is some progress towards achieving development goals, reducing 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, along with other factors that reduce vulnerability to climate and other global changes (Edenhofer et al., 2010).

Table 1. Overview of the scenarios

Scenario	**Description**	
	Socio-economic characteristics	Climate
Reference		
Reference	Population and income continue to grow at “business-as-usual” trends – **SSP2**	Climate conditions resemble weather patterns of early 2000.
Alternative socio-economic scenarios		
Alternative SSP	Low population growth in the OECD countries, moderate income growth, high income inequalities between OECD and non-OECD countries – **SSP3**	As in Reference
Alternative climate scenarios		
Scenario 1	As in Reference	Future climate RCP 8.5 calculated by **IPSL**; impacts on crops calculated using **LPJmL** crop model
Scenario 2	As in Reference	Future climate RCP 8.5 calculated by **Hadley**; impacts on crops calculated using **LPJmL** crop model
Scenario 3	As in Reference	Future climate RCP 8.5 calculated by **IPSL**; impacts on crops calculated using **DSSAT** crop model
Scenario 4	As in Reference	Future climate RCP 8.5 calculated by **Hadley**; impacts on crops calculated using **DSSAT** crop model

The socio-economic assumptions play an important role in assessing future agricultural markets. For illustrative purposes, an *Alternative SSP* scenario that uses different assumptions about population and GDP growth – the standardised scenario *SSP3* – is also analysed in this report. This scenario is characterised by slow growth in the rich countries, little convergence in incomes across countries and rapid population growth. Figure 1 shows the differences between the *Reference* and *Alternative SSP* scenarios in terms of their assumptions about population and GDP per capita. In both of these scenarios, populations remain constant or even decrease compared with 2010 in many high-income OECD countries. Globally, this is more than offset by the population growth in non-OECD countries, such that the total population is projected to reach 10 billion people. With the exception of Canada, GDP per capita in OECD countries is lower in the *Alternative SSP* scenario than in the *Reference* scenario.[3] Per capita income in regions such as sub-Saharan Africa and Southeast Asia are also approximately 50% and 40% lower, respectively, in the *Alternative SSP* scenario compared to the *Reference* scenario. In addition, average global income per capita is 60% lower in 2050 in the *Alternative SSP* scenario compared to the *Reference* scenario.

Figure 1. Population and GDP per capita change between 2010 and 2050 for selected OECD countries and world



Source: Calculated from IIASA/OECD (2013), https://secure.iiasa.ac.at/web-apps/ene/SSPDB.

The **climate scenarios** use the same socio-economic assumptions that are used in the *Reference* scenario. They differ in their projections of changes in regional precipitation and temperature levels resulting from changes in emission concentrations as calculated by two global circulation models (GCMs). These projections are then fed into two crop models that calculate the impact of changing temperatures and precipitation on crops. The results from these models are then used to inform the economic models about changes to average yields.

The two alternative climate scenarios are based on the so-called Representative Concentration Pathway 8.5 (RCP 8.5) (van Vuuren et al., 2011b; see also Annex B). RCP 8.5 assumes that concentrations of GHGs in the atmosphere increase slightly more quickly than current trends to 2050. As a result, RCP 8.5 projects that emissions in the second half of the 21st century will be substantially higher than current emission trends indicate, creating very high GHG concentration levels. Consequently, radiative forcing reaches 8.5 W/m^2 by 2100, resulting in an increase in the average global temperature of between 4 and 7 degrees Celsius. In addition, no CO_2 fertilisation effect is included. Therefore, a scenario based on the RCP 8.5 assumptions can be characterised as a strong climate change scenario. On the other hand, other factors such as rising sea levels or biotic stresses are not included, reducing some potential negative effects.

However, the climate effects in 2050 based on RCP 8.5 are not substantially stronger compared with those based on the lower concentration paths RCP 4.5 and RCP 6.0. The

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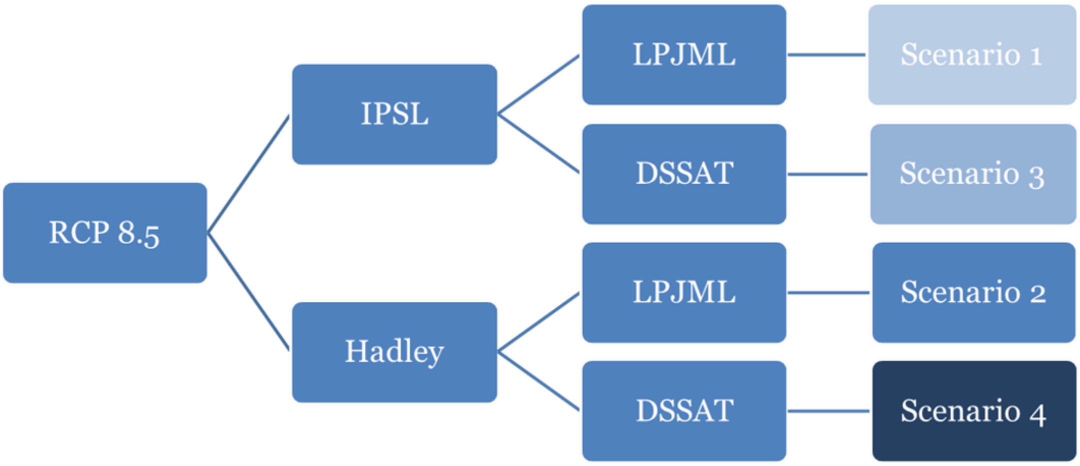
[3] High fuel prices boost Canadian GDP in the *Alternative SSP* scenario.

average temperature by 2050 for all three scenarios as a result of the concentrations of GHGs already in the atmosphere, and assuming limited mitigation efforts, is projected to be between 1.5 and 2.5 degrees Celsius higher than in preindustrial times.

This analysis uses two different GCMs – IPSL and Hadley (Johns et al., 2006) – to calculate future climate states. These GCMs project changes in the monthly averages of regional temperatures and precipitation. The results from the IPSL and Hadley GCMs then feed into 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 on specific crops (11 arable crops in the LPJmL model; rice, wheat, maize, soybeans and groundnuts in the DSSAT model). Combining the different climate and crop models results in four alternative scenarios, as shown in Table 1 and in Figure 2. Since these scenarios share all other assumptions with the *Reference* scenario, the specific effects of climate change on agriculture can be analysed by comparing these climate scenarios to the *Reference* scenario.

Figure 2. Schematic overview of the climate scenarios



3. Socio-economic impacts on agriculture

Global demographic and economic trends affect how much and what sort of food will be consumed. Whether increased agricultural productivity and increased use of land for agriculture will be able to meet growing (and changing) demand will be crucial in determining the future price levels of agricultural commodities. A wealthy population demands, on average, more nutritional and caloric food than a poorer population. Therefore, if future income levels are expected to increase and the middle class to grow, then prices of higher-value crops, dairy products and meat may increase. Additionally, with an increase in education and income levels, it may be expected that environmental awareness will increase as well. Some environmentally friendly technologies, including sustainable intensification of agriculture, organic methods of production and agroforestry, may also increase production costs, which would translate into higher food prices. But more investments in the agricultural sector may also take place, resulting in more efficient and more sustainable production and, consequently, in higher aggregate yields. Increased demand for ethanol and biodiesel may increase the demand and price for grains and oil seeds while also indirectly increasing the prices for other crops owing to increased competition for land.

A more pessimistic view about socio-economic developments may alter perspectives about 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 would have net positive impacts on the environment is unclear. On the one hand, the pressure to acquire new land for production purposes may imply that some nature areas, including primary forest, would be converted into agricultural land. On the other hand, the demand for foods rich in protein, such as red meat, may be lower, substantially reducing the demand for livestock products, thereby indirectly reducing demand 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 using the IMPACT model. The results present possible futures but need to be interpreted carefully.

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

Under the *Reference* scenario, prices for the majority of agricultural commodities are projected to increase by 2050 (Figure 3). This is mainly driven by increased demand as the global population increases by 2 billion within the next half century. An evident price increase is observable for high-protein commodities such as beef and poultry: by 2050, prices increase by 23% and 18%, respectively. These results are driven mainly by an increase in the global middle class and the corresponding demand for more meat and higher-quality food. The larger demand for meat triggers an increased demand for feed. This has an effect on the price of maize. An increase in demand for bioenergy also increases demand for maize. As a result, the price of maize increases by 38%. The prices of other staple crops remain 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.

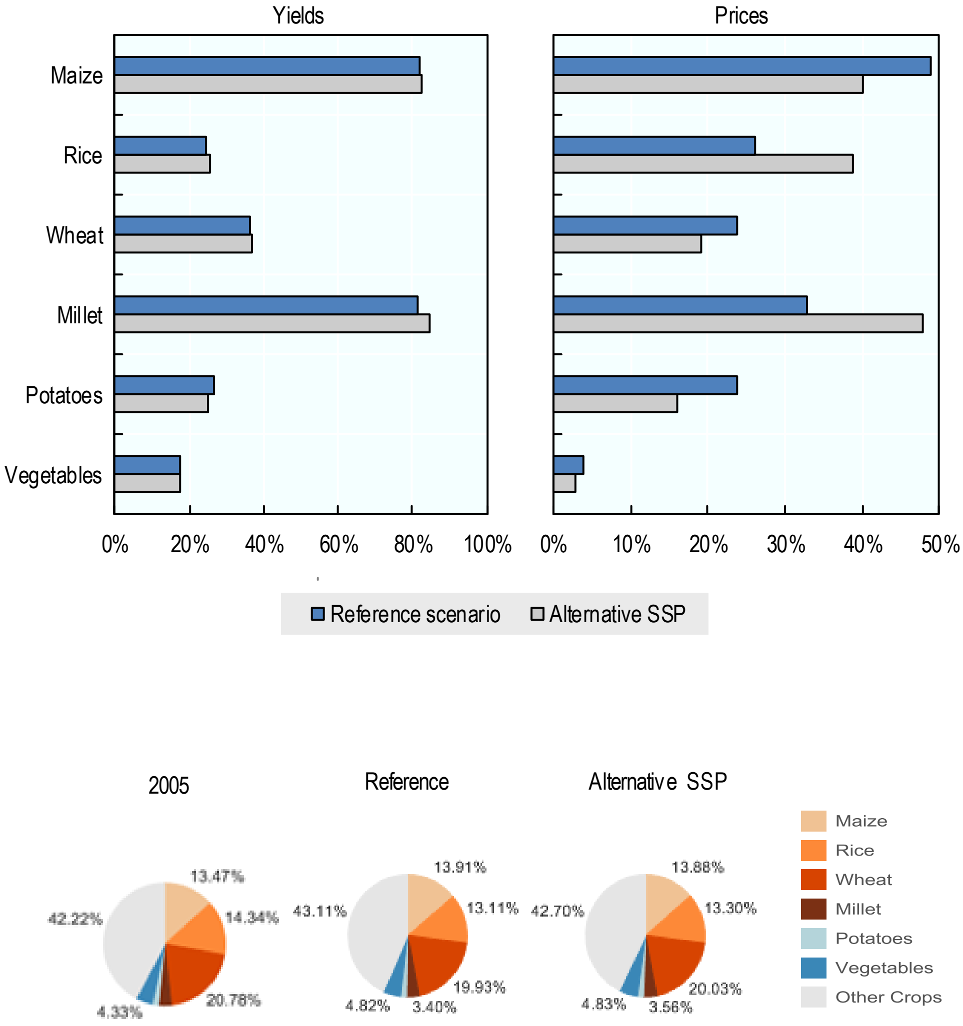
Following historical trends, improvements in yields are expected to continue, although less rapidly than previously. Globally, most of the improvements in yields will occur in developing countries, especially in regions where there are large differences between the current and the potential yield levels. Millet, a crop grown mainly in Africa and India, is expected to nearly double its yield by 2050 compared to current levels (see Figure 3). In OECD countries, an increase in maize yields may be expected, but the growth in yields is likely to be limited to about 1% annually (Figure 4). For crops such as wheat and rice, modest yield increases are anticipated in the *Reference* scenario.

Despite the continuous increase in yields, the pressure on land increases. In high-income countries, the land area given over to agriculture is expected to remain constant; in contrast, the increased demand for food in developing countries will increase pressure on land, causing the area under agriculture to be increased. By 2050, under current policies, an additional 10% to 15% of land may be used for agricultural production. The trend in the expansion of land use for agriculture is partly based on historical information and assumptions about other changes to land use, including urbanisation and expected changes in the size of forested areas. It is assumed that land use will be allocated to maximise profit.

The trends discussed above may change when different assumptions about population growth and wealth are made. In the *Alternative SSP* scenario, lower average incomes and higher population growth rates are assumed. Compared with the *Reference* scenario, prices of agricultural commodities in the *Alternative SSP* scenario are lower, albeit with some exceptions (Figure 3). Prices of staple commodities, especially those that have relatively high market shares in Africa and Southeast Asia, where the highest population growth is assumed to occur, are higher under the *Alternative SSP* scenario. These regions experience the largest difference in per capita income. Poor households, in reaction to decreased incomes, may spend less on nutritious food, including meats and vegetables, and more on basic foods such as rice, millet or sweet potatoes. In this scenario, the prices of maize and wheat still increase by 2050, but the increase is less pronounced than in the *Reference* scenario due to a substantial decrease in demand for these crops as feed.

In this more "pessimistic" setting, yields are assumed to increase at the same rate as in the *Reference* scenario. Overall, land allocation follows demand patterns, but a larger share of land is allocated to growing staple grains in the *Alternative SSP* (see the pie charts in Figure 3). Yields are, in fact, lower for maize and wheat in the *Alternative SSP* scenario, but not dramatically so: about 1% lower in the OECD region. In the *Alternative SSP* scenario, maize is used less for animal feed and more for direct human consumption. However, owing to a less pronounced transition towards high-protein food in developing countries, the demand for land to grow "staple" foods such as rice, millet, sorghum and cassava increases.

Figure 3. World price, yield and area changes of a selection of agricultural commodities in 2050 compared with 2005



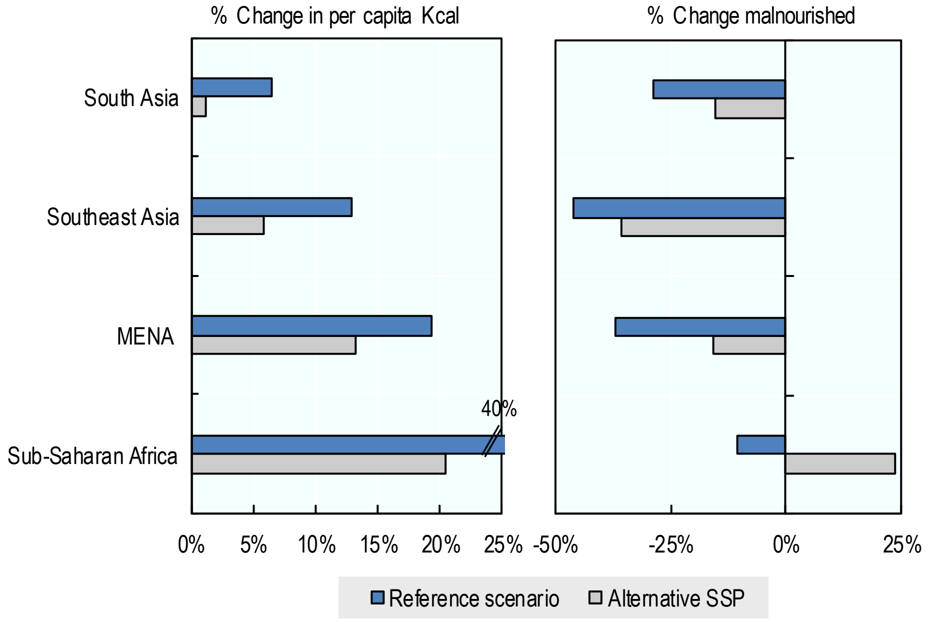
Source: Own calculations based on IMPACT simulations.

3.2. Food security

Various policies, such as investments in education and transportation and storage infrastructure, are being established in order to reduce hunger and poverty. Recent food price spikes have shown, however, that food security remains a serious concern around the world. Especially sensitive to food price volatility are countries in sub-Saharan Africa, South and Southeast Asia, and the MENA region, where a substantial share of the population does not have secure access to food. Two indicators have been chosen to highlight potential food security issues in these regions: i) the availability of calories consumed per capita; and ii) the proportion of malnourished children (defined as those aged between 0 and 5 years of age)[4].

Figure 4 shows that for virtually all regions in both the *Reference* and *Alternative SSP* scenarios, the available number of calories per capita increases in 2050 as compared to 2005. This also has indirect positive consequences on the potential number of malnourished children. The increased availability of calories is driven by significant income increases in all regions, especially in the least developed countries. In countries with high-income inequality, such improvements may be muted. The expected income level in the *Alternative SSP* scenario is lower on average than in the *Reference* scenario; therefore, the benefits in terms of higher calories consumed are less pronounced.

Figure 4. Change in food consumption per capita and change in the number of malnourished children in 2050



Source: Own calculation based on IMPACT.

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 increase in income levels. 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

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[4] The methodology used for calculating the proportion of malnourished children is based on Smith and Haddad (2000).

region. This suggests that income growth and population pressures are major constraints to achieving food security in the region.

4. Climate change impacts on agricultural markets

Climate change will likely affect food production in both direct and indirect ways, which will often create complex interactions that are difficult to analyse in isolation. Although CO_2 concentrations may be uniformly distributed across the globe, changes in temperature and precipitation levels is expected to vary among regions. Besides inter-regional variability, inter-annual and seasonal variability will also likely be altered. The magnitude of change is, however, highly uncertain.

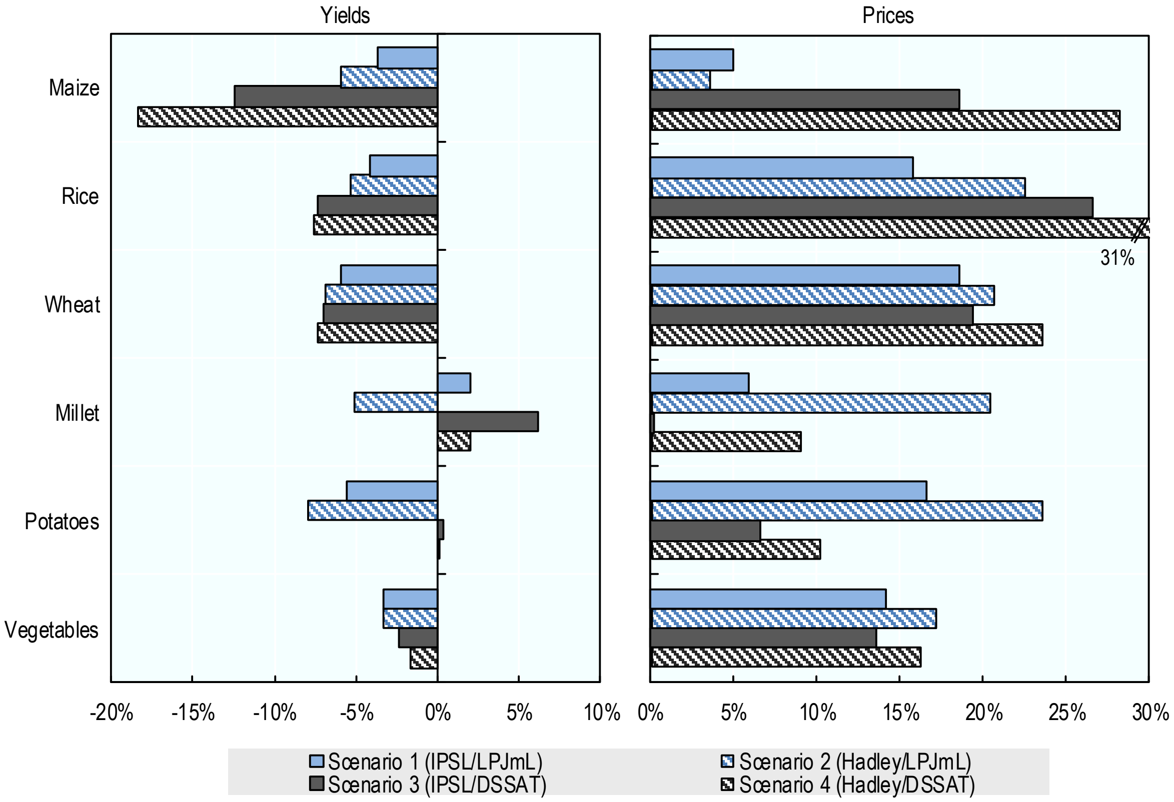
Another source of uncertainty arises from the reaction in biophysical processes to changes in temperatures and water availability. Crop yields show a strong correlation with temperature change and with the duration of heat or cold waves, and they differ based on plant maturity stages during extreme weather events. Similarly, crops are sensitive to both droughts and to an excess of water. In an indirect way, a change in temperature and moisture levels may lead to a change in the absorption rate of fertilisers and other minerals, which determine final yields. Crop yields are also likely to be affected by changes in the patterns and intensity of incidences of weeds and pests. Climate change is likely to affect the livestock sector both by affecting the quantity and quality of feed and by affecting the frequency and severity of extreme climate events. There is a limited body of literature that deals with climate change impacts on livestock, although there seems to be agreement that the livestock sector may be particularly vulnerable to the effects of climate change (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. Compared to the *Reference* scenario, the prices of principal agricultural commodities are higher under the “climate change” scenarios using the IPSL and Hadley climate models (Figure 5) as a result of lower crop yields. The prices of major grains such as maize, wheat and rice are, on average, between 5% and 30% higher when climate effects are included in the model.

Grains are, in general, vulnerable to heat and water stress, although grains such as millet, which are intrinsically more drought tolerant, may perform better than other grains. Figure 5 shows the projected impact of climate change on yields in 2050. For the three main crops, the climate change scenarios project yields that are lower than those that are projected in the *Reference* scenario, albeit less than 7% lower in most cases. Although, on average, climate change may have a negative impact on yields, the projected yields by 2050 are still higher than current yields for most commodities. In the case of maize, for instance, under *Scenario* 4, climate may reduce the potential yields by almost 20%, however the maize yields are still expected to be about 50% higher than they were in 2005. The two scenarios that use inputs from the DSSAT crop model (*Scenario 3* (IPSL/DSSAT) and *4* (Hadley/DSSAT)) result in higher world prices for maize, wheat and rice than do the two scenarios using the LPJmL crop model (*Scenario 1* (IPSL/LPJmL) and *2* (Hadley/LPJmL)). This suggests that the DSSAT model assumes that grains are more sensitive to increased temperatures. The two scenarios that use the LPJmL crop model (*Scenario 1* (IPSL/LPJmL) and *2* (Hadley/LPJmL)) project larger decreases in yields for potatoes and vegetables.

Figure 5. Change in world prices and yields of a selection of agricultural commodities in 2050 compared to the *Reference* scenario under different climate assumptions



Source: Own calculation using IMPACT.

Livestock prices show secondary effects of climate change as a result of increased feed prices. The price of beef and poultry is projected to increase by between 3% and 5% as a result of climate change. It is worth noting that IMPACT does not model the direct effect of heat and drought on either animals or on pasture productivity. Taking these effects into consideration would probably further increase the prices of beef and poultry.

4.2. Regional effects of climate change

The effects of climate change on various crops naturally vary across regions. Although climate change is expected to have a negative impact on yields in the majority of cases, in a few cases a boost in yields may be expected, as shown in Figure 6. Figure 7 presents the changes in land allocation relative to the *Reference* scenario.

Climate change will negatively affect the yields of rain-fed crops more than it will affect the yields of irrigated crops. In 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. In rain-fed agriculture, the only water available is that which the plants can access from the topsoil.

In general, *Scenarios 3* and *4*, which are based on input from the DSSAT crop model, show higher negative effects on grain yields. This observation is consistent with results of the

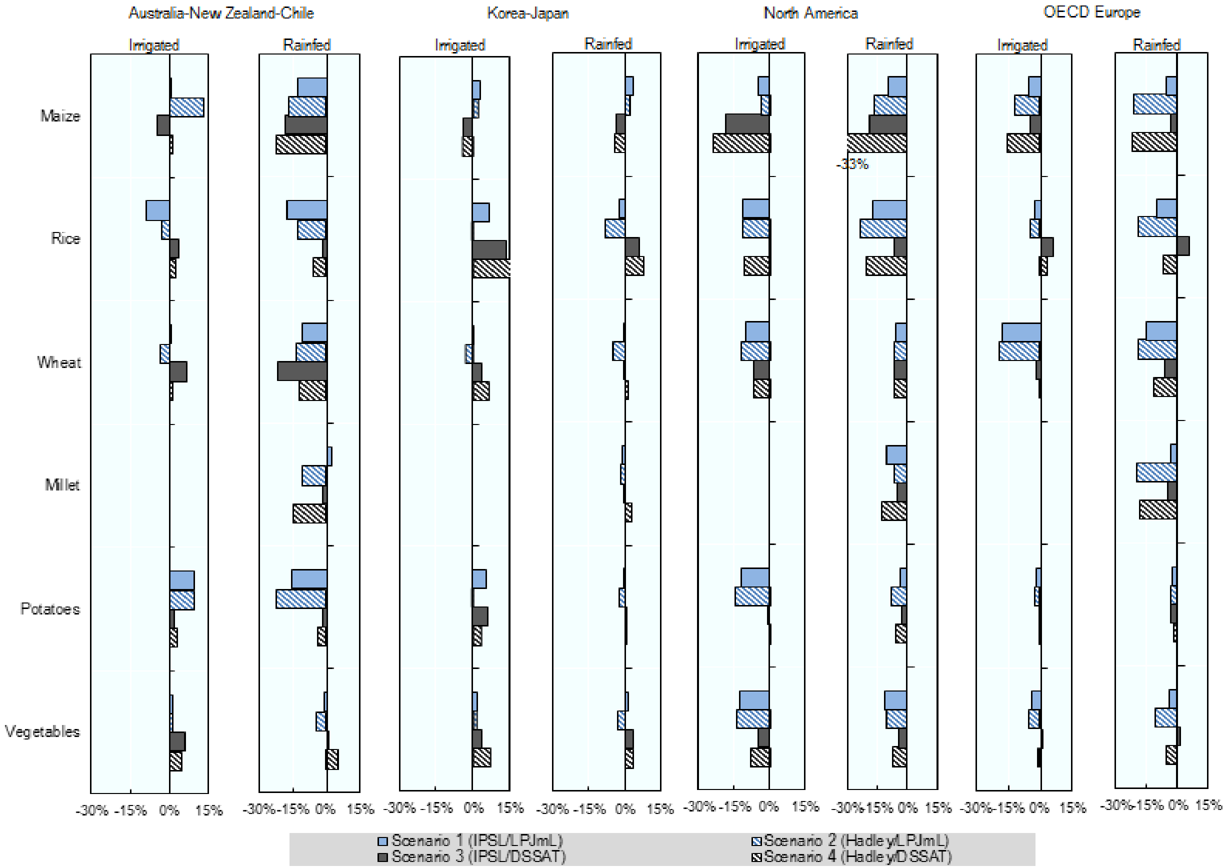
AgMIP model comparison, where in general, models that used inputs based on DSSAT assumptions showed larger effects from climate change (von Lampe et al., 2014; Nelson et al., 2014). Differences between the IPSL and Hadley GCMs are not especially pronounced, even if these models present contradictory results for some regions. For instance, the scenarios featuring the IPSL GCM show positive changes in maize yields in southern Europe, whereas the scenarios using the Hadley GCM show lower yields, compared to the *Reference* scenario. This can be explained by the fact that IPSL projects increased rainfall in southern Europe, whereas Hadley assumes a decrease in rainfall.

Despite the negative effects of climate change on agricultural production, all of the modelled scenarios project that OECD countries will remain net exporters of food in 2050. The United States remains a large net exporter of maize, although it reduces its exports to around half of its current value in the *Reference* scenario. Many developing countries remain net importers of food, and some increase their net imports of food. For instance, under *Scenario 3* (IPSL/DSSAT), India’s domestic maize and wheat production decreases and its imports of these commodities increase by approximately 40% and 50%, respectively, compared to the *Reference* scenario. Sub-Saharan Africa remains a net food importer across all of the scenarios.

The potential negative effects of climate change do not imply, however, that there will be a large relocation of agricultural production by 2050. Land allocations remain similar to their current form. In OECD countries, wheat continues to be produced predominantly in Europe and Australia, while maize is produced in North America and rice in Korea and Japan (Figure 7). The IMPACT model shows relatively modest effects on land expansion in comparison to other models included in the AgMIP project. Some other models, such as ENVISAGE, AIM and GCAM, show much greater 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.

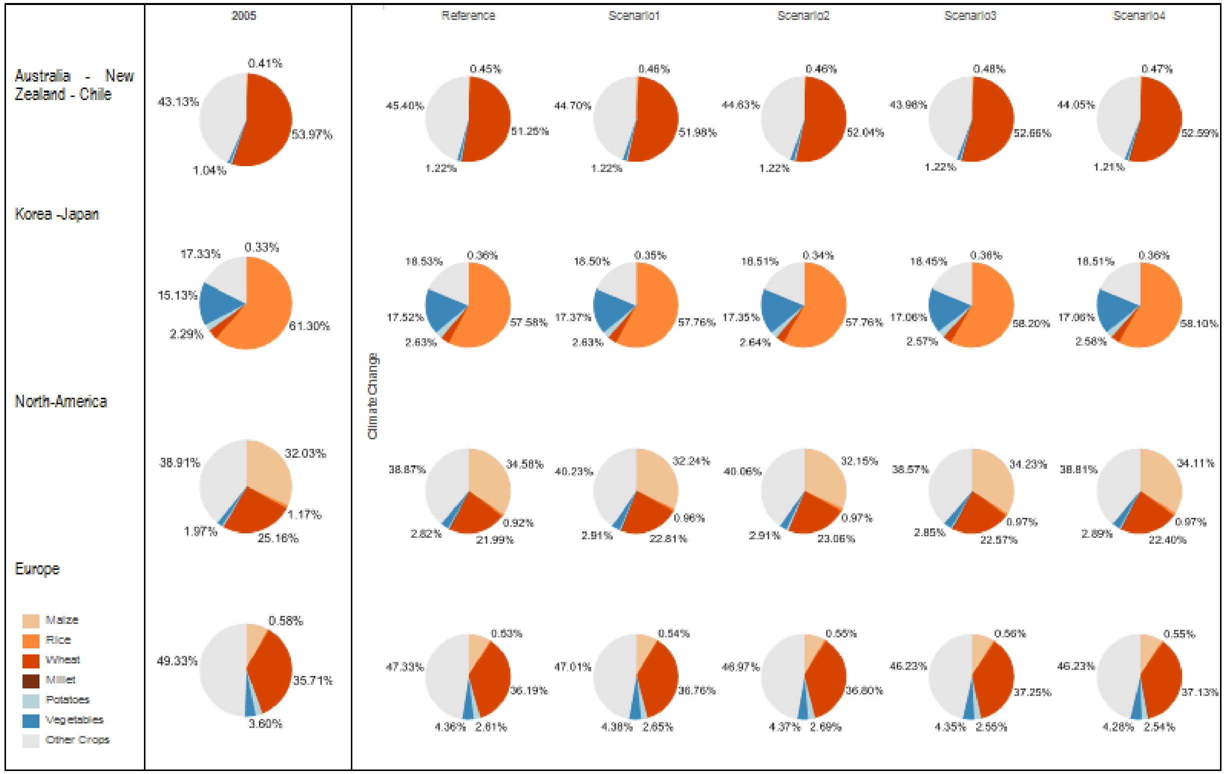
Crop yields in developing countries are likely to be affected even more by climate change. Sub-Saharan Africa and the Middle East and North Africa regions in particular, although projected to have the largest increase in productivity growth rates, lose potential gains as a result of the effects of climate change. Nevertheless, in general, despite large negative climate effects, the yields in these regions are still expected to be higher than currently.

Figure 6. Changes in yields of a selected set of commodities in irrigated and rain-fed areas



Source: Own calculations based on IMPACT simulations.

Figure 7. Changes in land allocation within OECD countries

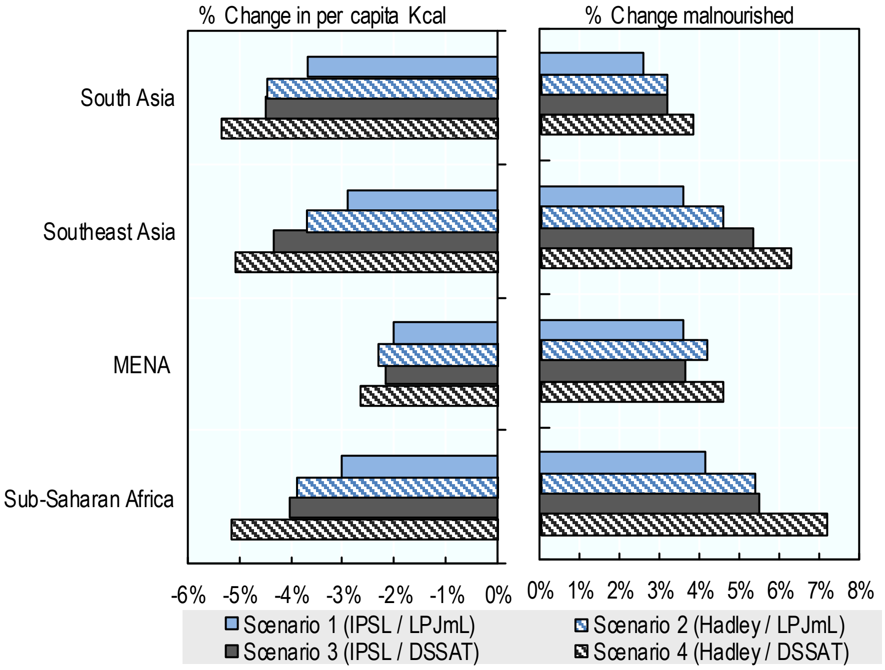


4.3. Climate change effects on food security

Although the general intake of calories increases by 2050 compared to 2005 levels, and the number of children who are potentially exposed to hunger decreases in absolute level, climate change is likely to have a negative effect on food security in the future, reducing the food security improvement that would have otherwise occurred. Compared to a situation without climate change, the four "climate change" scenarios modelled in this study project large changes in future yields, resulting in increased threats to food security in many developing countries.

Figure 8 presents changes in calorie consumption per capita in 2050 and changes in the number of malnourished children due to climate change in the modelled scenarios as compared to the *Reference* scenario without climate change. Aggregate consumption decreases in all regions in all four of the modelled scenarios. The loss of calories per capita due to climate change ranges between 2% and 5% compared to the *Reference* scenario.

Figure 8. Climate change impacts on food security in 2050 compared to the *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

The results in this study show that in the most negative climate scenarios, the yields for many critical food crops could be lower by more than 30% in some regions by 2050. This would have obvious impacts on food availability. To explore some of the adaptation technologies that could be pursued to mitigate these negative effects, two types of scenarios have been developed. The first focuses on developing improved crop varieties that are more tolerant of heat and drought. The second considers the role of various irrigation management strategies. By no means do these two sets of measures present an exhaustive list of possible adaptation measures; rather, they are 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 same countries that have achieved higher growth rates in their agricultural Total Factor Productivity (TFP) (Fuglie and Wang, 2012). This same study notes that technological improvement has become the most important factor in increasing agricultural production, in contrast to other factors such as increasing use of fertilisers or expanding agricultural land. Goldfray et al. (2010) suggest that there is significant potential to increase crop yields through improved conventional plant 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 functioning properly and farmers have access to high-quality seeds (OECD/FAO, 2012). It is important to note, however, that there may be a higher cost associated with using such technologies.

Nonetheless, with a changing climate it is important to direct investment towards those crop varieties that are able to withstand the increasing abiotic stress caused by changes in temperature and precipitation, as well as other changes that climate changes could cause indirectly, such as changes in pest and disease patterns (Vermeulen et al., 2011). Currently, several research organisations are working to develop new or improved crop varieties with greater resilience to the effects of climate change. Privately funded research centres are becoming more active in this field as well. One needs to be careful, however, to maintain the genetic variations in 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 the efficient use of irrigation water. A strong call to recognise the importance of improving the efficiency of water and soil use in a sustainable manner by the agricultural sector was made by G20 leaders and G20 Agricultural Vice Ministers in May and June 2012. Since then, the OECD and several other international organisations have identified a set of policy recommendations to make water use in agriculture more efficient and to improve water supply infrastructure, including by increasing investments in these areas. These strategies are discussed in more detail in Annex B.

The results of each of these general adaptation measures (agricultural R&D and water management) are uncertain. Therefore, two different scenarios for agricultural R&D and three scenarios for water management were designed in order to analyse some of the potential challenges and effects of various assumptions. Table 2 summarises these adaptation scenarios, which will be discussed in more detail in the following subsections. Each of these five adaptation scenarios are tested in the *Reference* climate scenario and in each of the four modelled climate scenarios (*Scenarios 1-4*) that were discussed in the previous section (these adaptation scenarios were not tested using the *Alternative SSP* model). As a result, 25 adaptation scenarios are considered below.

Table 2. Overview of adaptation scenarios

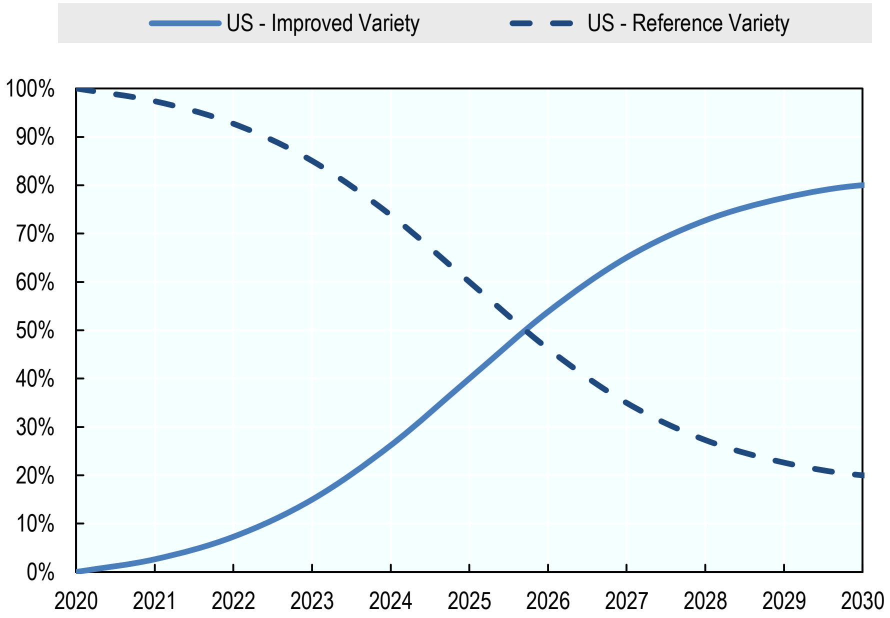
Adaptation Scenarios	Description	
	Measure Specification	Regions and Timing
Research and Development		
R&D	**Improved** production **technologies** for maize and wheat are implemented in the United States. These improvements, including e.g. crop improvement and protection technologies, boost yields in maize and wheat by 10% and 5%, respectively, in relation to the assumptions in the *Reference* scenario.	Improved technologies begin to be adopted in the United States in 2020, reaching a maximum adoption level of 80% by 2030.
TT	**Technology Transfer** – Follows the R&D scenario with technology diffusion from the United States to other OECD countries.	The same as above for the United States. Adoption in the rest of the OECD member countries begins in 2023 and reaches a maximum adoption rate of 80% in 2033. No changes within non-OECD countries.
Water Management Scenarios		
EFF	**Irrigation Efficiency –** Improvement in irrigation technology in OECD countries leads to increased water use efficiency until all basins in the OECD reach a minimum efficiency of 72%.	Efficiency improvements begin in 2006 and end by 2050 in all OECD countries. No changes within non-OECD countries.
IR	**Irrigation Expansion** – Rain-fed areas transformed into irrigated areas in OECD countries as a result of investments in expanded irrigation infrastructure.	Expansion of irrigated areas grows at the same rate as basin efficiency improvement in the EFF scenario. No changes within non-OECD countries.
EFF+IR	Combines scenarios *EFF* and *IR*	Same as in the EFF and IR scenarios.

5.2. Modelling Research and Development

Two specific adaptation measures related to R&D are proposed and discussed in this section: *i)* R&D to generate improved crop production, and *ii)* technology transfer. These have been identified as important in reducing the potential negative impacts of climate change on agricultural production (OECD, 2008; European Environmental Agency (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 LPJmL and DSSAT 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 to be implemented in an optimal way. Without these autonomous measures, the impacts of climate change on yields would be greater.

To analyse the impact of newly developed varieties of maize and wheat that lead over time to higher growth rates in yields, a new (hypothetical) variety 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 the new variety is cost-neutral for farmers; however, in reality improved varieties may cost more compared to traditional varieties. As a caveat, the model assumes that there are no research costs related to developing this new technology and its development does not appear at the expense of other technology development or government expenditures.[5] These new varieties enter the United States market in 2020 and slowly increase their share compared to conventional technologies (Figure 9). It is assumed that the new technologies achieve a maximum adoption rate of 80% after ten years. Figure 9 shows the technology adoption rate of the new varieties.

Figure 9. Rate of the technology adoption in the United States over time



To investigate the role that technology transfer can play in adapting to climate change, a second set of adaptation scenarios assumes that the new technologies for maize and wheat are adopted by the rest of the OECD countries. This adaptation scenario assumes that the new varieties are adopted by other OECD countries at the same rates as in the United States beginning in 2023, allowing for a couple of years before technology diffusion begins. Figure 10 shows the two regional adoption pathways. Please note that the "learning" aspect of technology transfer would also create some costs.

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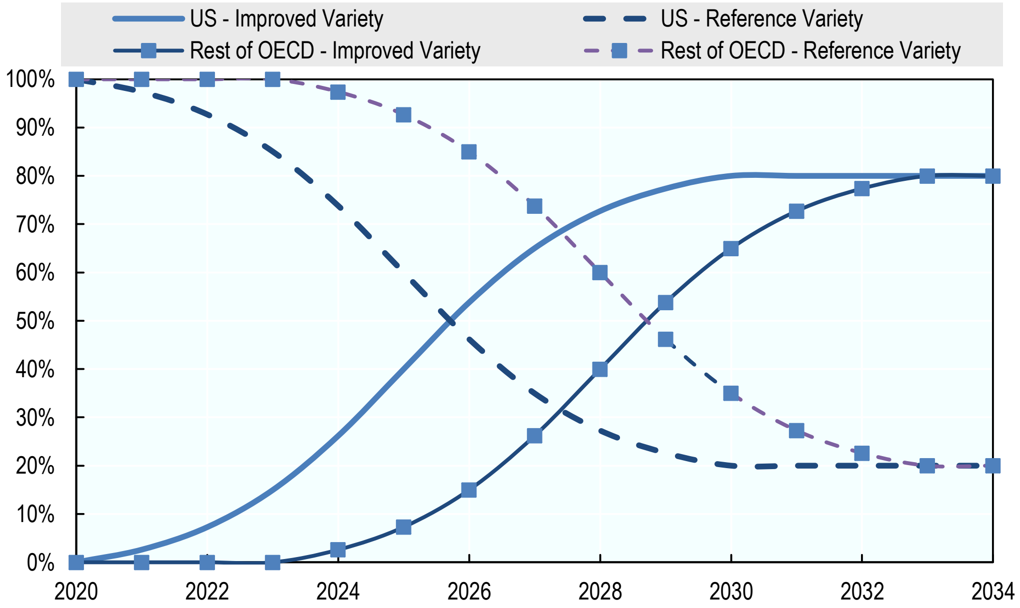
[5] Section 7 will discuss adaptation costs separately.

Figure 10. Rate of the technology adoption in the OECD



5.3. *Modelling water management strategies*

Yields on irrigated land are, on average, higher than on rain-fed land, which makes expanding irrigated agricultural areas a promising policy in response to both greater demand for food and to relatively greater stresses on production resulting from climate change. However, freshwater is not an infinite resource, and as such the expansion of irrigation, although potentially an important adaptation measure, would need to be implemented with care because water scarcity may increase as a result of greater demands for water from non-agricultural sectors, as well as to 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 efficiency[6] improves the use of current and future water supplies. Improved irrigation efficiency is modelled under a scenario where all of the basins in the OECD 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 24). This efficiency gain is assumed to increase linearly over the 45-year projection period, representing a slow but steady increase in irrigation efficiency. It should be noted that improved irrigation efficiency leads to improved yields only in circumstances of water shortage. It is a technology that can increase yields, 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 a rain-fed area into an irrigated area. Irrigating rain-fed areas is expected to lead to higher average yields, essentially changing the production technology in a manner that allows more intense production. The amount of land converted to irrigation was calculated by assuming that the water used to irrigate the newly converted land would match the amount of water "saved" as a result of improved water reliability in the first irrigation scenario.

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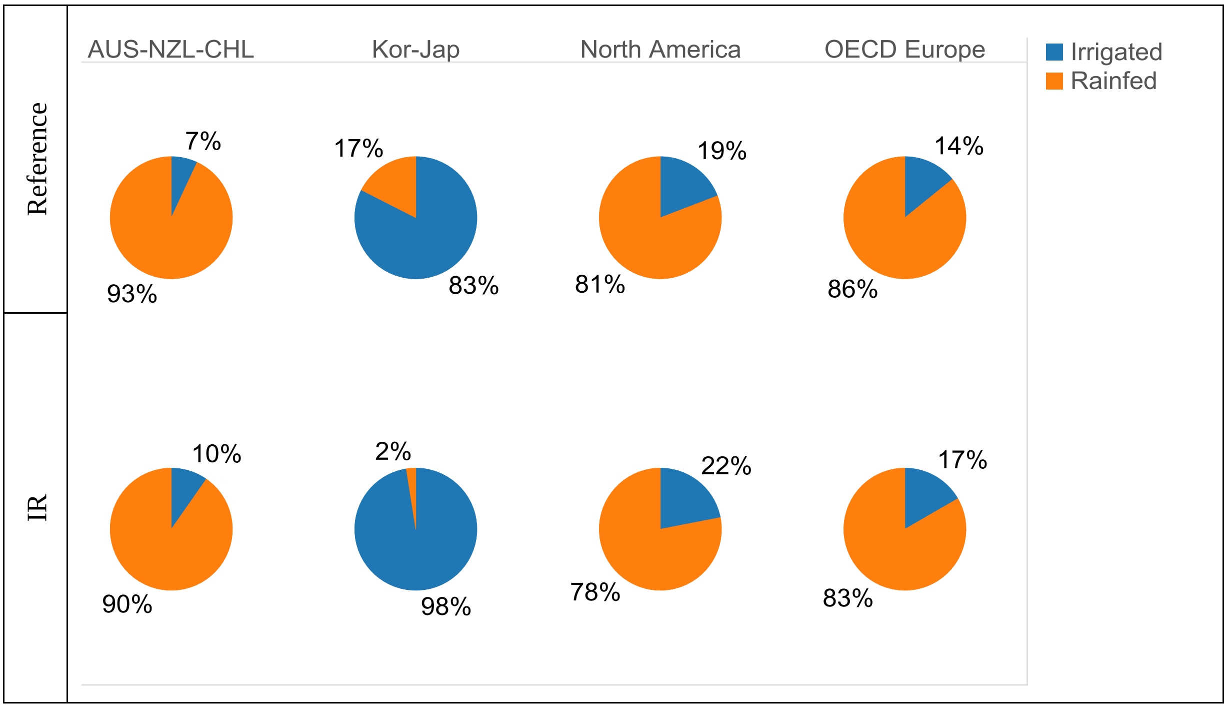
6. Irrigation efficiency equals the share of water that is effectively used by crops relative to water withdrawal rates for irrigation.

Expanding the area of irrigated land is bound to have a more direct effect on average crop yields than increasing irrigation efficiency. However, due to water constraints in some regions, it may not be possible to maximise yields in irrigated areas due to greater demand for water from other users. Figure 11 shows the different proportions of irrigated and rain-fed agricultural land in the four OECD regions in the *IR* and *Reference* scenarios. These results assume that the land area under agriculture remains constant at 2005 levels.

Figure 11. Changes in agricultural land use by 2050 in the OECD under the IR scenario



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

6. Results of modelling the adaptation scenarios

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

Under both the R&D and TT scenarios, yields increase significantly in the adopting regions compared to their respective climate change scenarios. In addition, there are also international spill-over effects. World prices for maize and wheat are lower by 3% and 1% respectively compared to scenarios where the improved varieties are adopted only in the United States, and by 4% and 2% respectively when adopted throughout the OECD (Figure 13).

Under the irrigation management scenarios, there are limited yield benefits from improved water efficiency in most OECD countries; the Mediterranean basin in southern and western Europe (namely France) is the exception. For those regions that are currently battling water stress, e.g. the Mediterranean, irrigation efficiency measures contribute to improved yields on the order of between 3% and 5% in irrigated areas growing mainly maize and vegetables.

Water stress becomes apparent when irrigated areas are expanded without increasing irrigation efficiency. Expansion of irrigated areas without improving irrigation efficiency results in lower average yields in southern and Western Europe (and in North American vegetable yields) due to increased water scarcity for irrigation. In all other regions, the expansion of irrigation leads to greater productivity as agriculture production benefits from having a larger proportion of more productive irrigated areas. When improved efficiency is coupled with irrigation area expansion, agriculture can further benefit as the reduced demand for water per hectare reduces the constraints on water use. Figure 12 illustrates the yield effects in the OECD when each of the five R&D and water management adaptation scenarios are combined with the *Reference* scenario and with each of the four climate change yield scenarios discussed in Section 3 (the *Alternative SSP* scenario is not included).

The results show that yield increases produced by all five adaptation scenarios lead to reductions in the world prices of the main crops (Figure 13). The largest price decreases for any specific commodity occurs in the R&D scenarios, which assume increases in maize and wheat yields. The price for maize decreases by more than 4% in the technology transfer scenario. While the largest single individual price change occurs under the R&D scenarios, the indirect effects of R&D on other commodities are very limited, with price reductions on the order of 0.25% to 0.5% for other commodities. Under the irrigation management scenarios, price decreases are spread more broadly, with price decreases of 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 R&D scenarios contributes to a slightly larger price reduction (albeit still less than 0.5%) for beef and poultry in the technology transfer scenario because of a decrease in the cost of feed.

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 14-16 illustrate the effects of price on land allocation in the two most positive adaptation scenarios (technology transfer in the first case, expanded irrigation combined with increased irrigation efficiency in the second case). Under the TT scenarios, the area under maize and wheat cultivation decreases by approximately 1%. Less area is needed to meet demand for maize and wheat, and this newly available land is converted to other commodities leading to an increase in the area 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. The production of any of these commodities therefore increases. Nevertheless, land allocation remains fairly steady in the water management adaptation scenarios, which should be expected as the relative price changes due to water management adaptation measures should not lead to dramatic changes in land allocation

Figure 12. Average yield change by 2050 due to adaptation scenarios

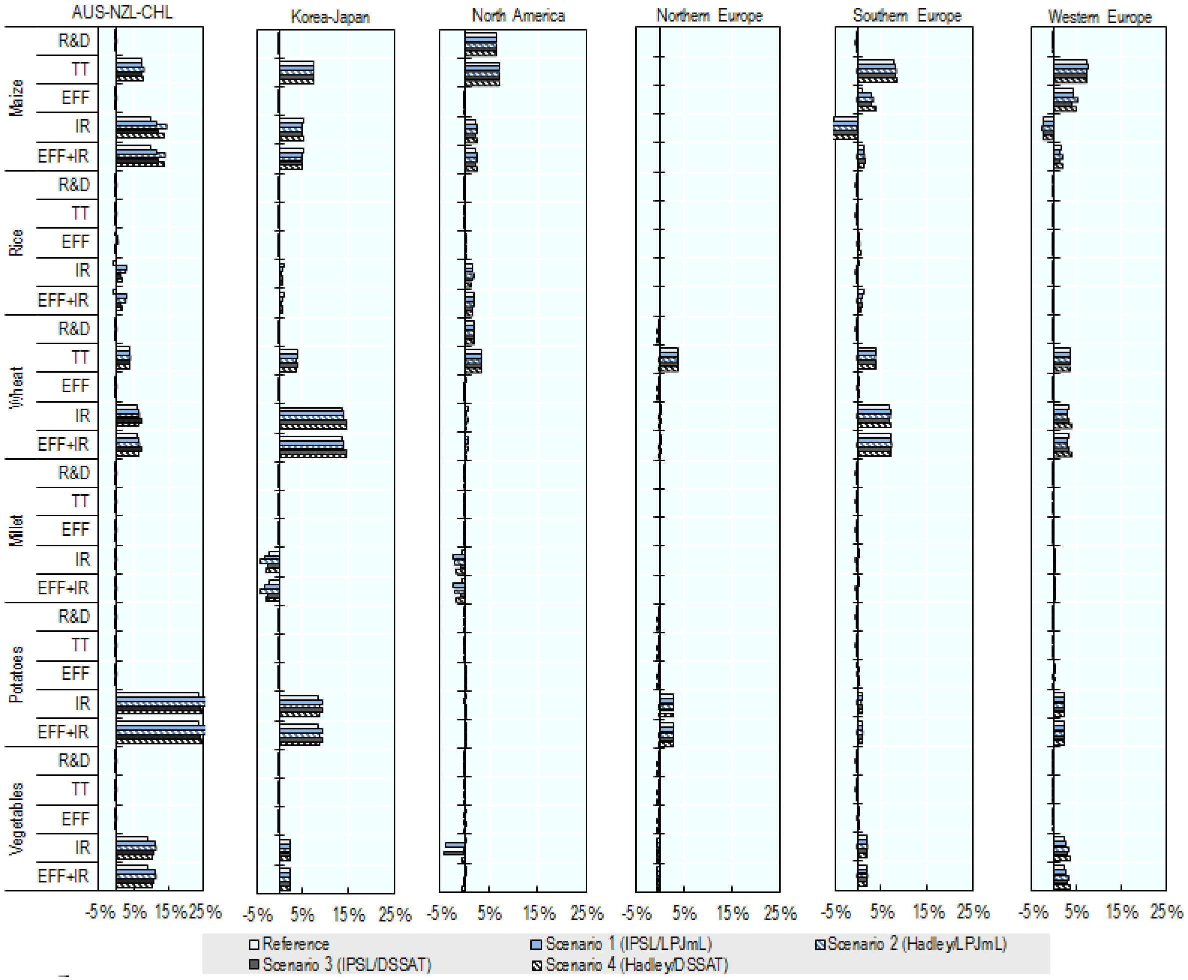


Figure 13. Price changes in 2050 by adaptation scenario compared to respective climate scenarios

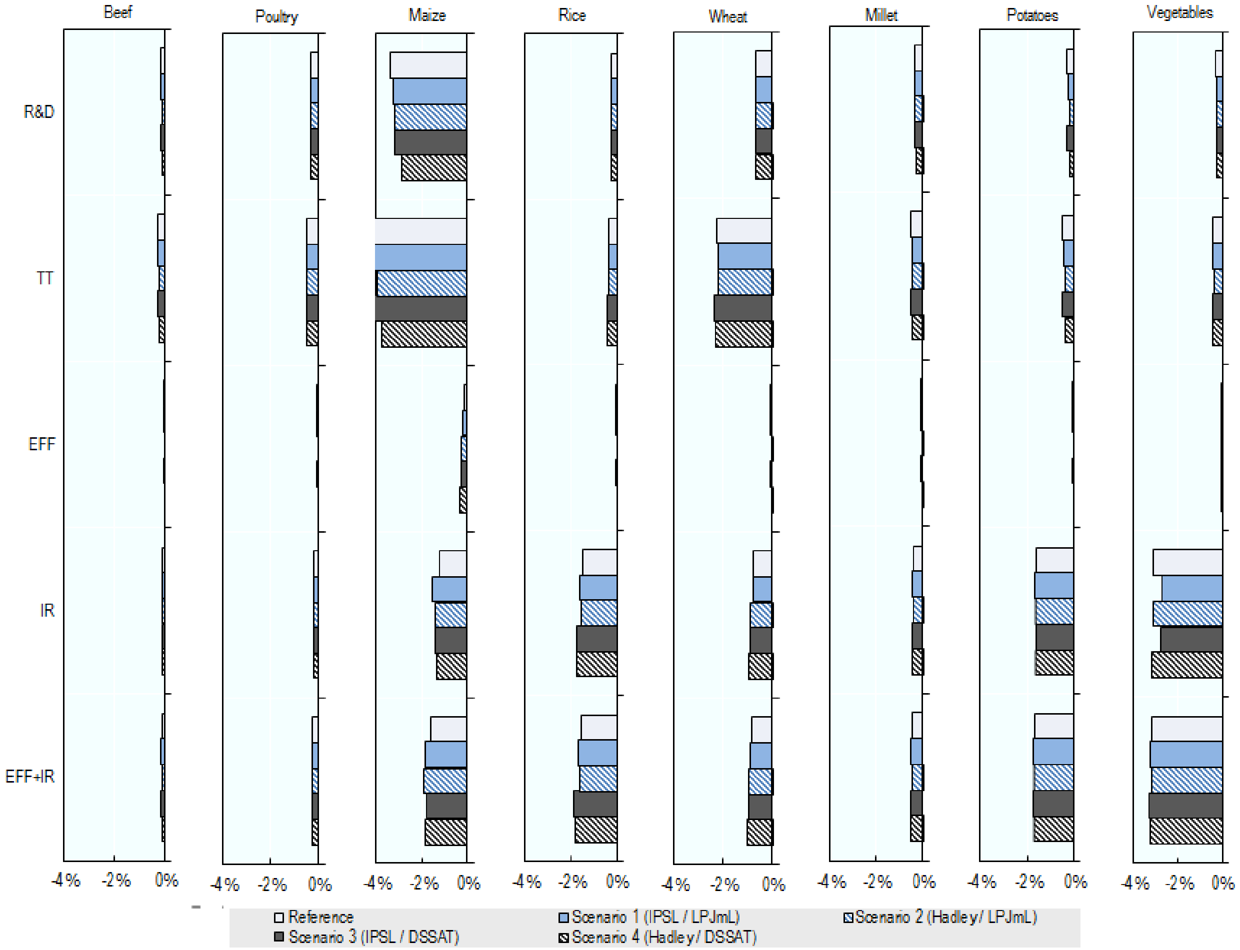


Figure 14. Changes in cultivated land areas for select commodities in the OECD from TT scenario

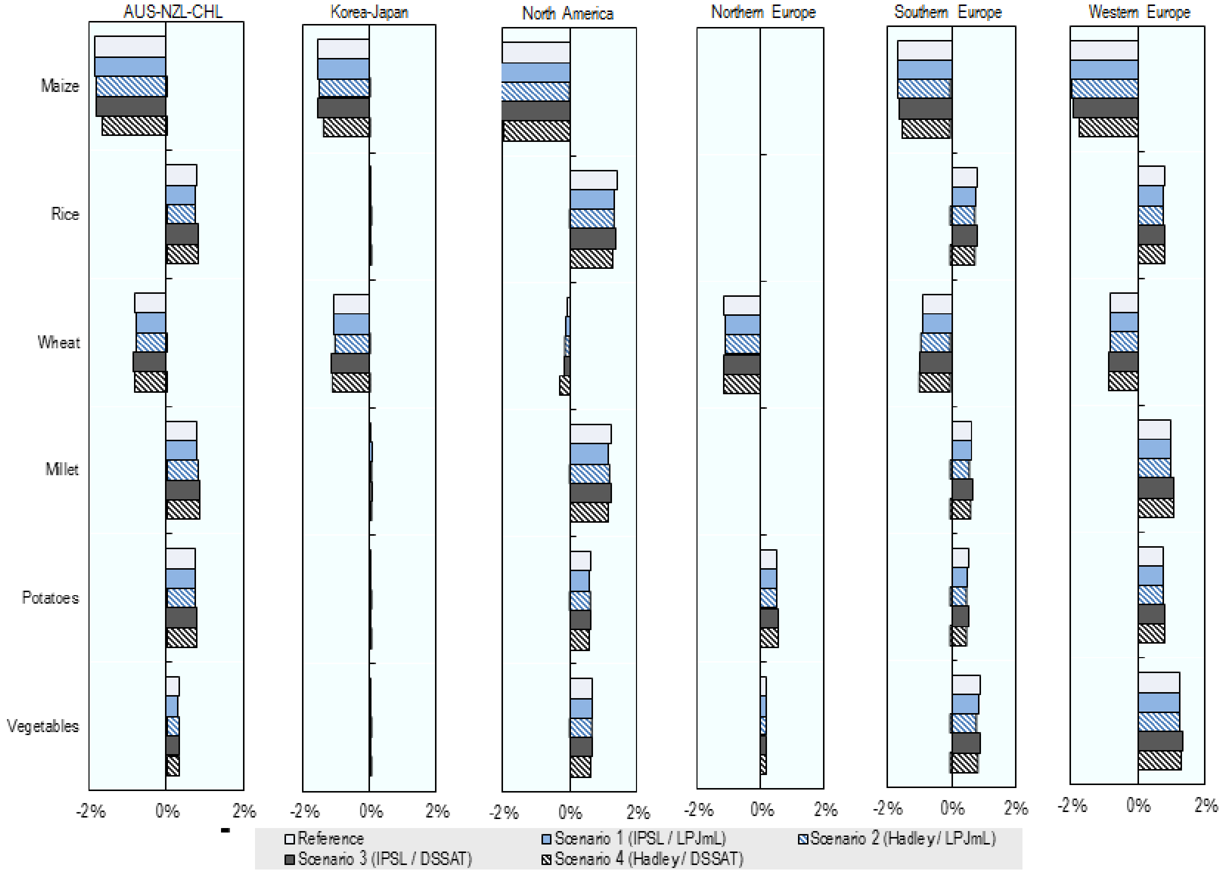


Figure 15. Changes in cultivated land areas for select commodities in the OECD from EFF+IR scenario

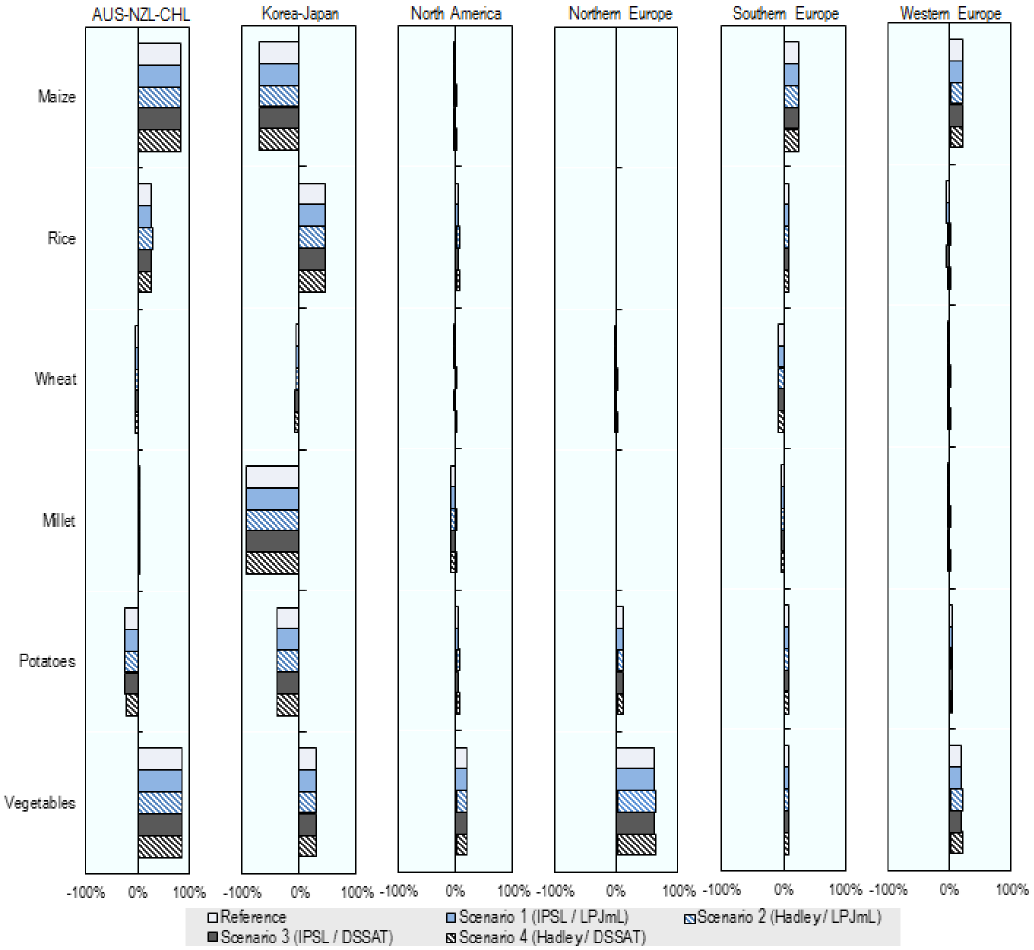
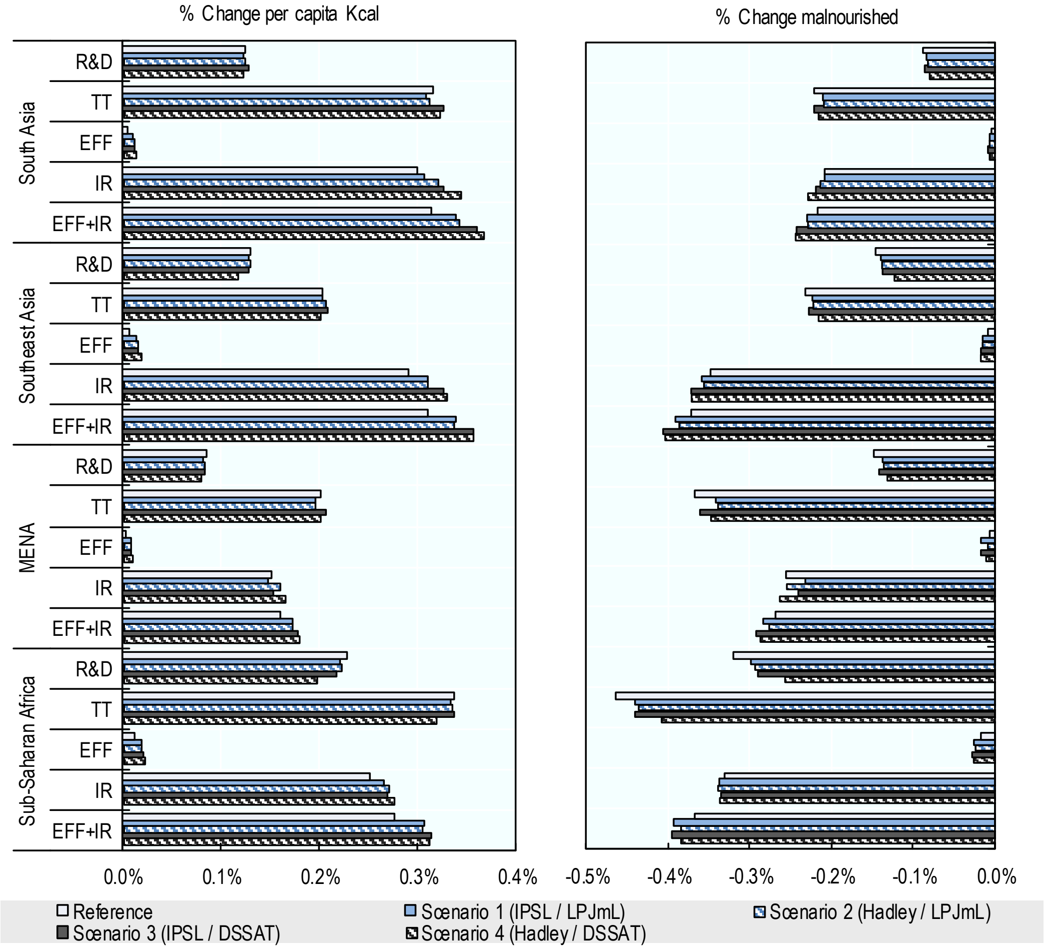


Figure 16. Changes in cultivated land areas for select commodities in the OECD for TT and EFF+IR scenarios

6.2. Impacts of adaptation measures on food security

Despite the effects of climate change, it is likely that overall food security improves in the next few decades as a result of increased agricultural productivity in both developed and developing countries, and of various policies to reduce poverty. If the adaptation measures are adopted in the OECD countries as a result of the price effect, the situation may improve further. Compared to a climate change scenario without adaptation, each of the adaptation scenarios implies a reduction in world food prices over the 45-year period to 2050. In relative terms, this reduction in food prices will increase 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 and lead only to small increases in food availability globally (less than a 0.5% increase), with a correspondingly small improvement in the rate of malnourishment (which decreases by less than 0.5%). Thus, while these scenarios help mitigate some of the effects of climate change, they do not fully mitigate potential food insecurity in developing countries.

Figure 17. 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 agricultural production in developing countries, as well as improving access to markets, will likely have a greater effect on reducing malnutrition globally than will those policies focused on increasing productivity in developed countries. Figure 17 summarises the observed changes in food availability (expressed in calories) and the resulting changes in the number of malnourished children for each of the five 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.[7] 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 owing 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 because they exclude investments that need to be taken at the regional or national 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 OECD countries. The analysis is by no means an attempt to provide a full picture of adaptation costs for the agricultural sector; instead, it aims to provide an estimate of the orders of magnitude of the potential expenditures that would be needed to support some adaptation measures. The purpose is also to complement the cost estimates provided by the World Bank in its 2009 Economics of Adaptation to Climate Change (EACC) study, where the costs of adaptation in agriculture were calculated for developing countries (Nelson et al., 2010). Based on the same methodology, this report presents the projected adaptation costs in agriculture for OECD countries. The EACC study considered three types of adaptive measures: (1) R&D, (2) water infrastructure and (3) roads. As inland and coastal infrastructure in OECD countries is well developed, the present analysis only deals with calculating the costs of additional expenditures in (1) R&D and (2) more efficient irrigation equipment (see Annex C for more details).

To estimate the cost of additional R&D necessary to offset the effects of climate change, this study assumes that climate change would cause a 50% reduction in yields by 2050.[8] The study also assumes that countries strive to reach 72% irrigation efficiency by 2050. This method is different from the method used by the World Bank. Due to the lack of a widely accepted adaptation metric, the World Bank uses the number of malnourished children as a measure of adaptation. More specifically, the World Bank calculates the level of investment in agriculture that is required to prevent an 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 change dramatically in different climate change scenarios, this study used different benchmark measures.

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

[8] In case of the United States, the proposed adaptation measure offsets about 50% of the potential loss in maize yields in *Scenario 4* (Hadley/DSSAT). For this illustrational purpose, the overall R&D costs are calculated based on the assumption that they may also offset 50% of potential yield losses in other OECD countries.

The methodology used to estimate additional R&D expenditures is based on a function of the estimated elasticity of changes in expenditures relative to changes in yields. First, a baseline of expenditure growth in both private and public R&D to the year 2050 is established. Second, for a given scenario, a level of additional expenditure is calculated based on a required change in yields. The methodology to calculate the improvement in irrigation efficiency differs from the R&D measures. The adaptation expenditures are calculated as necessary investments in order to achieve the given minimum efficiency target for OECD countries. First, an initial efficiency rate is calculated based on the share of each irrigation technology used in each OECD country. Second, the proportion of an inefficient irrigation system that must be replaced in order to achieve a chosen level of irrigation efficiency is calculated. In addition, the annualised costs of the potential replacement irrigation system are calculated. A detailed description of the methodology is provided in Annex C.

The results of these computations show that the additional annual expenditures needed in agricultural R&D to reduce potential yield decreases due to climate change for OECD countries amount to between USD 2.3 billion and 4.5 billion for public R&D and to between USD 3.0 billion and USD 5.3 billion for private R&D (total R&D equals between USD 5.3 and 9.8 billion), depending on the climate change yield scenario used. Approximately 50% to 56% of additional agricultural R&D is expected to be carried out by the private sector, compared to the current rate of 45%. This suggests that offsetting a 50% potential loss in yields 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% irrigation efficiency target in all OECD countries are projected at USD 10.4 billion. The investment costs necessary to improve irrigation efficiency are higher than R&D costs, but because the effectiveness of each of these measures differs, it cannot be conclusively determined which measure is more cost-effective. In addition, these estimations should not be seen as precise cost figures but rather as indications of the potential costs when investing in specific technological measures to increase the efficiency of agricultural water use in OECD countries.

The total annual cost for implementing both the R&D and irrigation efficiency measures amounts to between USD 15.7 and USD 20.2 billion, depending on the climate change/crop yield scenario used, as shown in Table 3.

There are only a few global studies that provide estimates of the adaptation costs 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. Furthermore, making a direct comparison between these different estimates is difficult because the effectiveness of measures varies across the studies.

Figure 18 shows selected regional estimates of the adaptation costs in agriculture. Although it is impossible to compare these estimates due to different approaches, and to different regional aggregations, and because the low number of available studies does not allow for thorough analysis, some general observations can be made. One observation is that adaption costs will be high. The only study that both provides an estimate for autonomous adaptation costs and accounts for transition costs 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 (de Bruin (2013)). Another general finding is that all models indicate that delays in implementing adaptation programmes increases the costs of adaptation. A third observation, unsurprisingly, is that in more severe climate change scenarios (or, as in some models that assume that mitigation actions are absent or weak), more adaptation investments are needed to compensate for the larger negative effects of climate change.

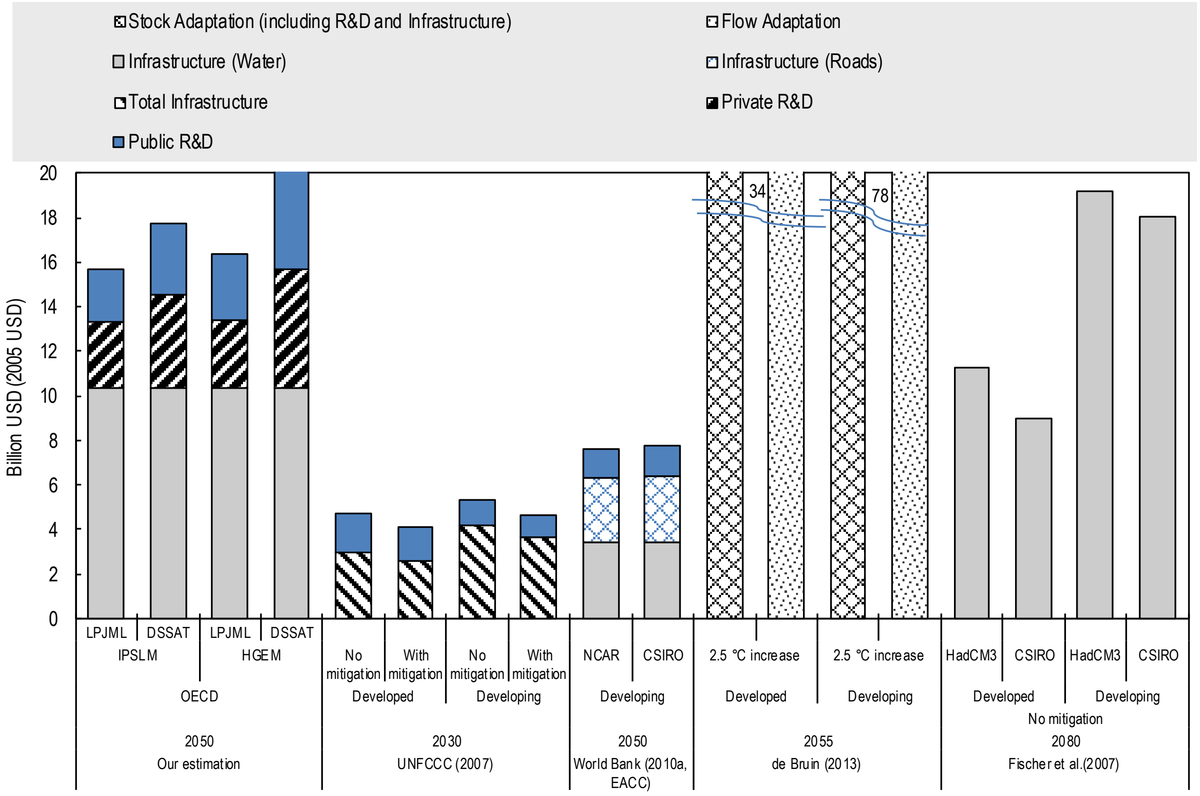
Table 3. Estimates of the average annual adaptation costs (2010-2050) in OECD countries for R&D and irrigation efficiency in billions of US dollars*

Scenarios Costs	*Scenario 1* (IPSL/LPJmL)	*Scenario 2* (IPSL/DSSAT)	*Scenario 3* (Hadley/LPJmL)	*Scenario 4* (Hadley/DSSAT)
Total R&D	5.3	6.0	7.4	9.8
Public R&D	*2.3*	*3.0*	*3.2*	*4.5*
Private R&D	*3.0*	*3.0*	*4.2*	*5.3*
Irrigation efficiency	10.4	10.4	10.4	10.4
Total	15.7	16.4	17.8	20.2

* In 2005 USD.

Source: Own calculation.

Figure 18. Global estimates of adaptation costs in agriculture (average annual cost 2010-2050)



Source: Own compilation.

Box 1. Review of existing estimates of regional costs of adaptation to climate change

UNFCCC

In 2007, UNFCCC estimated the costs of adaptation for six sectors, including agriculture, to the year 2030 (McCarl, 2007). The global annual cost of adaptation in agriculture is estimated at between USD 7.8 and 8.9 billion; for high-income countries, the costs are estimated at between USD 3.7 and 4.2 billion. This incorporates both public and private expenditures. The total costs of adaptation in agriculture is based on 1) the 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 corresponding food requirements (McCarl, 2007).

The assessment is based on historical trends and different climate scenarios. The "business as usual" scenario assumes no climate change. Two climate change scenarios assume: *i)* no mitigation (SRES A1) or *ii)* some mitigation (SRES B1). In the first climate change scenario, the UNFCCC assumed a 10% increase in research and extension funding and a 2% increase in capital formation, while the second climate change scenario assumed an 8.6% increase in research and extension funding and a 0.4% increase in capital formation.

World Bank

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 that approximately USD 7.6-7.7 billion is needed annually for agricultural adaptation measures in developing countries until 2050.

Two climate scenarios based on the SRES A2, "no mitigation and high population growth" scenario are used and compared to the "business as usual" scenario in which current climate conditions are assumed to continue. One of the main indicators used in this study is the number of malnourished children. Climate change negatively affects food security and in both of the climate change scenarios used by the World Bank, the number of undernourished children increases by 2050. The cost of adaptation is estimated by assuming that public investment in the agricultural sector can maintain the number of malnourished children in these scenarios at the same level as in the "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

Neither of the estimates above incorporates 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 through the end of this century. For developed countries, stock and flow adaptation costs together are estimated to amount to USD 68 billion, of which USD 34 billion is needed for autonomous adaptation. For developing countries, adaptation costs were calculated at USD 156 billion, of which USD 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 maximising the regional utility function in each period where consumption and savings/investments are endogenously chosen subject to income and the costs of climate change. Climate change costs include 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 crop yield variation information from the FARM model.

IIASA

Fischer et al. (2007) estimates the cost of additional irrigation water requirements caused by climate change from 1990 to 2080 using the Agro-ecological zoning (AEZ) model developed by the Food and Agriculture Organization (FAO) and the International Institute for Applied Systems Analysis (IIASA). The global annual costs of additional irrigation were estimated to reach USD 24 to 27 billion by 2080, where the additional annual cost is USD 8 to10 billion for developed countries and USD 16 to 17 billion for developing countries. Climate mitigation action is expected to reduce the total cost to USD 16-17 billion, which would be a reduction of USD 3 to 4 billion for developed countries and of USD 5 to 6 billion for developing countries. In the mitigated scenario, the annual costs for increasing irrigation capacity are estimated to be USD 8 billion in 2030 and USD 12 to 14 billion in 2050.

In addition to the "business as usual" scenario, climate scenarios were constructed using different assumptions regarding mitigation actions: *i)* a no mitigation scenario and *ii)* a 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 as a proxy of partly mitigated climate. Comparing the climate scenarios with the "business as usual" scenario 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 that climate change may induce. Although the scenarios presented in this report offer only a stylised representation of possible 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 in stimulating positive impacts where applicable). Autonomous adaptation measures such as choosing different inputs that are more appropriate to new climate conditions, improving on-farm water retention in soils or altering the timing of cropping activities can increase the resilience of food systems. These “good practices” may, however, be insufficient to reduce the risks posed by climate change. Thus, additional adaptation measures may be necessary. This report shows in particular that developing improved seed varieties, transferring technology and improving irrigation systems can make agriculture more resistant to changing climate conditions.

Providing access to new technologies can help spread the use of more resistant seed varieties and improve global food availability. Additionally, the spill-over of using productivity-enhancing technologies for particular crops may reduce their prices globally, thereby increasing food affordability, although on a limited scale. The widespread adoption of crop varieties that are resistant to the projected 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 infrastructure, 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 in emissions continue. These costs depend strongly on the projected adaptation level, and the marginal costs must always be evaluated against the marginal benefits they deliver. Due to the lack of common metrics to measure the effectiveness of adaptation, it is impossible to determine optimal adaptation strategies. Under the assumptions used in this study, the potential additional costs in R&D and in improved irrigation technologies are estimated to reach USD 16 to 20 billion per year by 2050 for OECD countries. These estimates fall 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.

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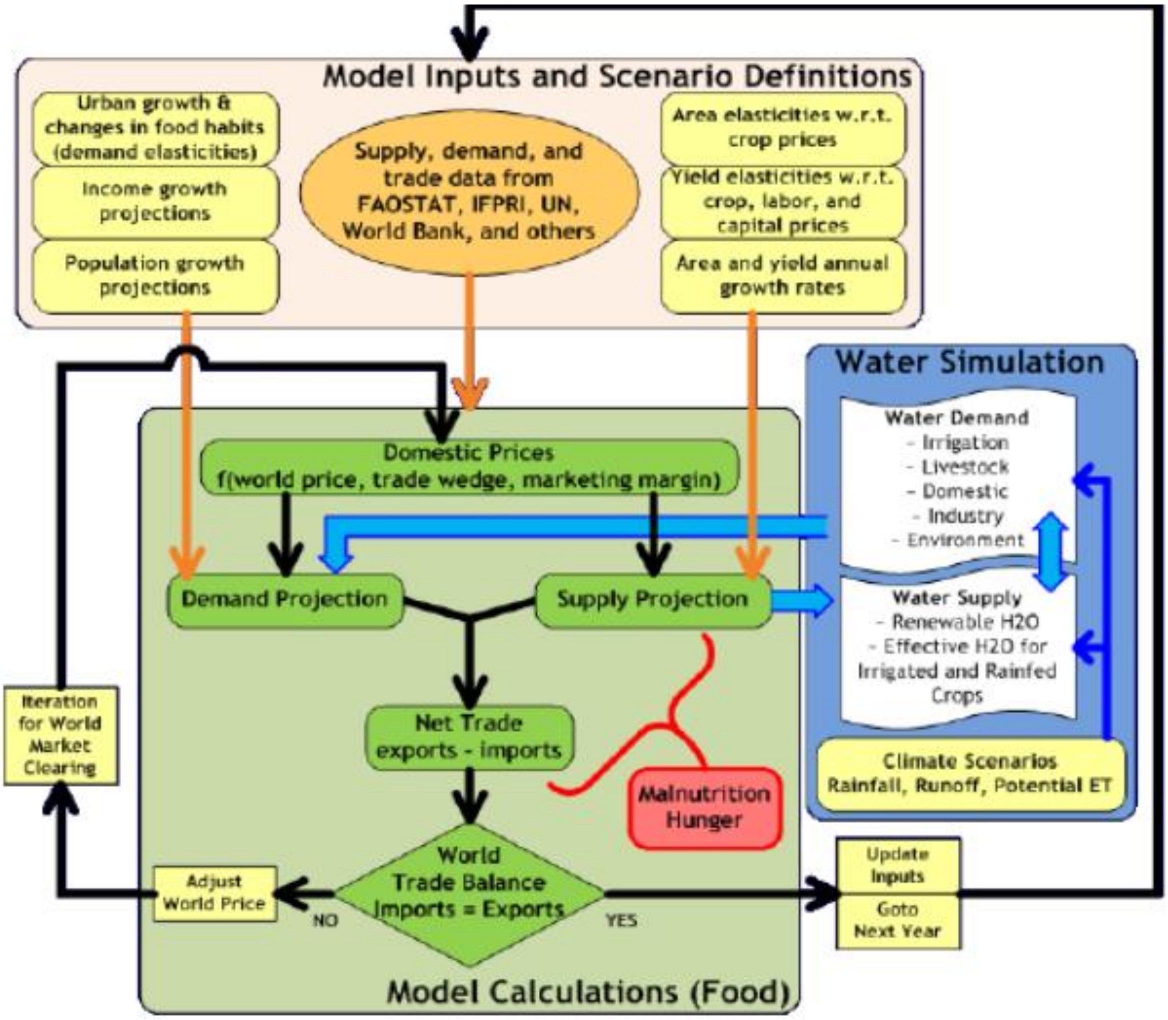
Annex A.

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 combines a partial equilibrium model and a hydrological model. The partial equilibrium agriculture model emphasises policy and trade simulations, while the hydrological model simulates water systems and water stress. IMPACT is linked to specific external biophysical crop models. This suite of models was developed to project global food supply and food security over the medium and long term (Rosegrant et al., 2012). Figure A.1 presents the schematic overview of the IMPACT model.

Figure A.1. Schematic model description



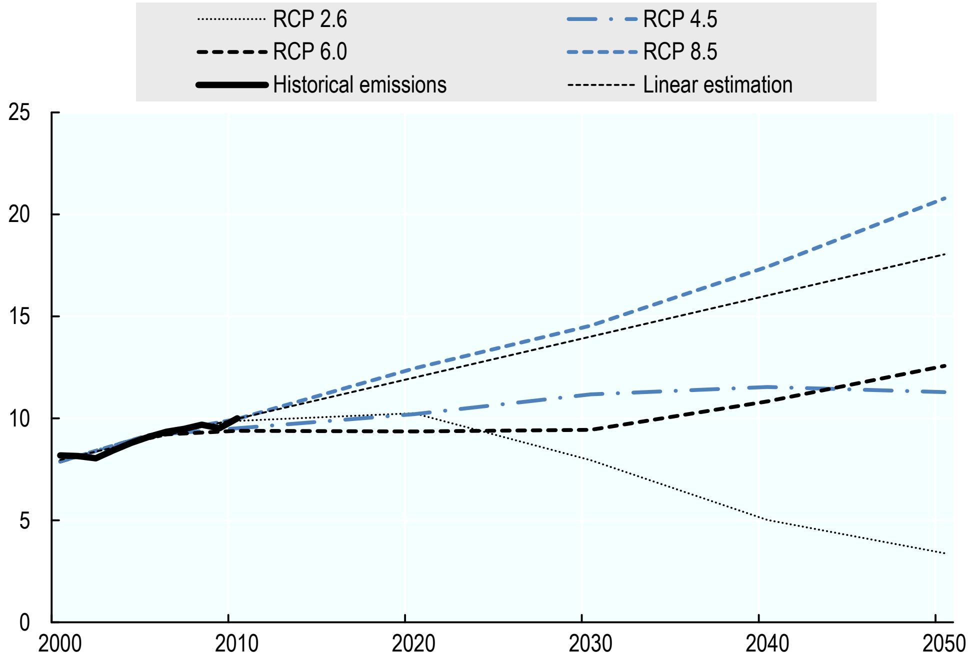
Source: Rosegrant et al. (2012).

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 level (defined within 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 rain-fed and irrigated areas, taking into account specific land and water conditions. Some countries, such as the United States, have several food production units within their borders, while smaller countries are often aggregated within one food production unit, e.g. Belgium and Luxembourg. The major drivers of agriculture supply are the price levels of all crop and livestock commodities. Aggregate demand is a function of price, GDP and population, and comprises 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 price changes for these commodities, as well as changes in the prices of substitutes and in their own income levels (Nelson et al., 2010; Rosegrant et al., 2012).

The water module in IMPACT **computes the amount of water available to irrigate farmland** after assessing water demand for the domestic (urban), industrial, environmental and livestock sectors. This is then used to calculate the potential yield shock if there is insufficient water to satisfy agricultural demand. To incorporate 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 the responses of five important crops (rice, wheat, maize, soybeans, and groundnuts) to changing biophysical conditions, and 2) the Lund–Potsdam–Jena managed Land (LPJmL) model to simulate the responses of 11 arable crops (Bondeau et al., 2007).

Both of these biophysical crop models need detailed information about current, base year and future climate conditions to the year 2050. To provide some idea of the uncertainties inherent in climate change simulations, the results from two different general circulation models (GCMs) are used as alternative climate condition scenarios in this analysis. The first of these was developed at the Institute Pierre Simone Laplace (IPSL model); the second is the Hadley Centre Global Environmental Model (Hadley model) from the MET office, the national weather service in the United Kingdom (Johns et al., 2006). Both models are being used to project future climate scenarios in preparation for the fifth Assessment Report of the IPCC. They calculate "representative concentration pathways" (RCPs), which project the concentration of greenhouse gasses in the atmosphere, taking into account a range of factors that determine future climate change (such as 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, 2011b). Figure A.2 presents the emissions pathways for four RCPs, as well as the historical emissions trend (GCP) and its extrapolation to 2050.

Figure A.2. CO_2 emissions for four representative concentration pathways and current emissions trend in pgc/yr (2000-2050)



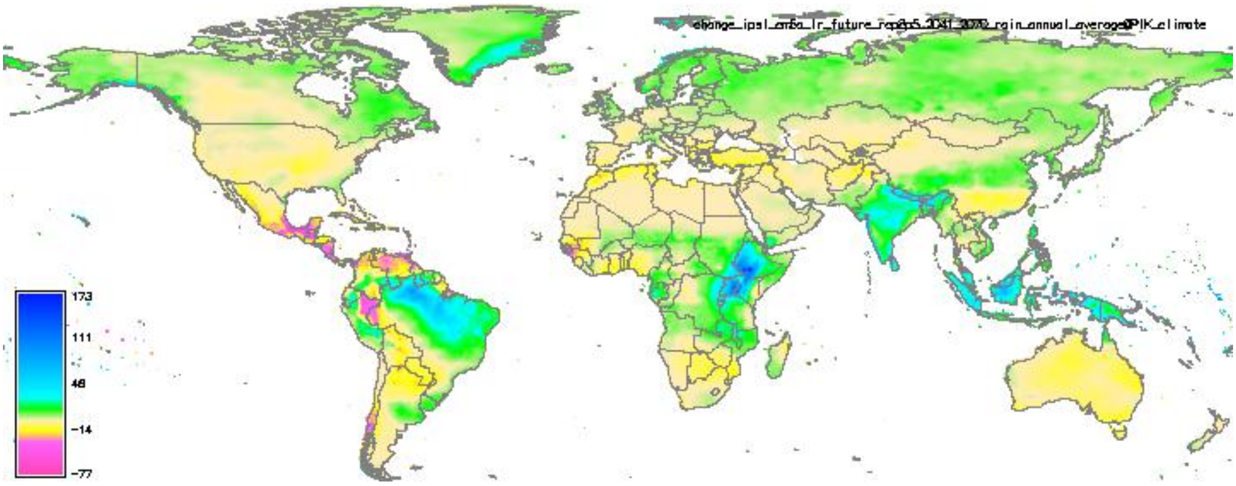
Source: IIASA (www.iiasa.ac.at) and GCP (www.globalcarbonproject.org/). Models that calculated these emissions paths are: IMAGE, MiniCAM, AIM and MESSAGE for the 2.6, 4.5, 6.0 and 8.5 RCP respectively.

Both the IPSL and Hadley climate models show clear changes in precipitation patterns as compared to the "climate of 2005", as was noted in the previous section where the *Reference* scenario was discussed (Figures A.3 and A.4). In general, both climate models project the high latitudes in the northern hemisphere to be wetter. More precipitation is also foreseen for equatorial Africa and Asia. The IPSL model shows more distinctive changes than the Hadley model. For instance, for some regions of Kenya, IPSL shows an increase in average precipitation per month of more than 100 mm, while the Hadley model estimates an increase of about 10 mm per month. Large differences are also apparent in the models' projections for equatorial America: Where the IPSL model shows a significant increase in precipitation, the Hadley model projects a large decrease. Both models project that average temperatures will increase, although with some regional differences.

Incorporating projections for crop yields from the DSSAT and LPJmL crop models, as well as the water module, in the partial equilibrium economic framework of IMPACT, allows the combined effects of socio-economic and climate developments on agricultural production and future food availability to be assessed.

Figure A.3. Rainfall – changes in monthly average over whole year compared to reference – IPSL model RCP8.5

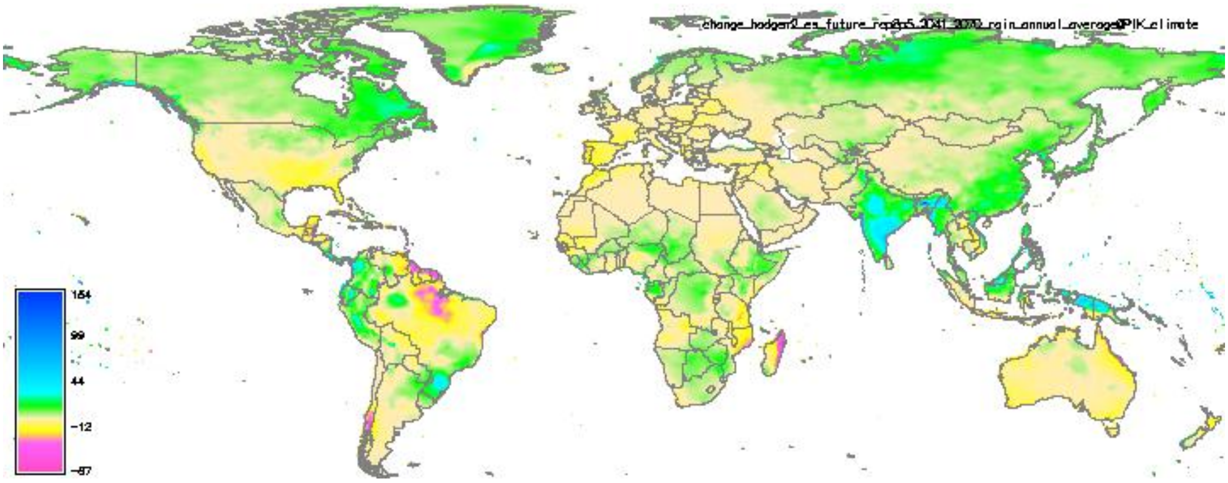
Mm/month



Source: DSSAT.

Figure A.4. Rainfall – changes in monthly average over whole year compared to reference – Hadley model RCP8.5

Mm/month



Source: DSSAT.

Limitations to the model

IMPACT comprises a complex suite of modules. Each module has strengths and limitations, which create differences in their numerical results. As in all models, IMPACT aims to be more detailed in those elements that are most central to the topic for which it is intended, e.g. it projects caloric intake from specific foods to determine the nutrition levels of children in developing countries, but is more stylised and aggregate in its projections in other domains. For this reason, a number of limitations in IMPACT's economic module need to be highlighted in the context of the present work.

Generally, all agricultural economic models feature simplified representations of the behaviour of various agents based on past observations and current expertise. As a consequence, scenarios for the (long-term) future cannot be seen as forecasts and should be interpreted with caution. The actual effects of exogenous shocks such as climate change may be quite different from the results produced 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 such as Aglink, IMPACT does not have a fully specified production function for each crop; thus, its representation of the possibilities available to farmers to switch between different production technologies is limited. Clearly, a good representation of technology switching is important when projecting adaptation to climate change. Nonetheless, the major technologies are specified in the model in a crop- and region-specific manner.

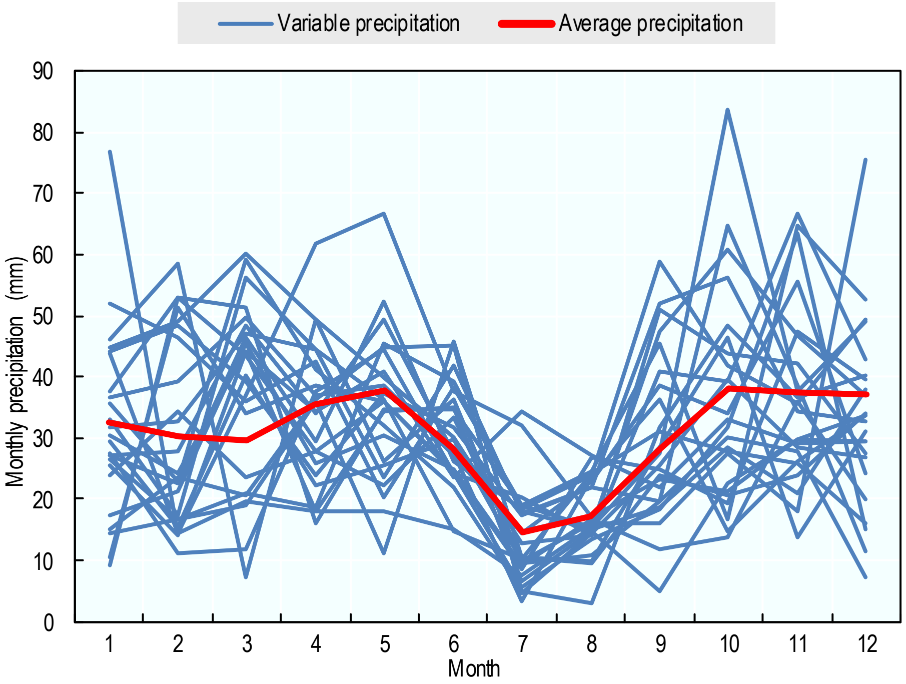
Third, land use in IMPACT is only associated with crop production. No other land use types are incorporated into the model, limiting its ability to fully account for land use changes. Note that this module of IMPACT is currently being revised. It should be noted as well that more comprehensive land use modelling may be envisaged by the OECD 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 in the water components would help improve its representation of the impacts of climate change. Areas to be explored include the role of weather volatility under climate change, as well as improved integration with crop models to improve the estimation of water stress. More nuanced linkages with other sectors' demands for water, such as livestock, would also allow for improved modelling of total water demand.

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

The representation of the effects of climate change is also stylised. For instance, the values of all climate variables are assumed to change linearly between in the years 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 will proceed linearly. This may underestimate the benefits of risk-reducing technologies such as irrigation efficiency and drought tolerance. It is also important to note that taking the average of the results of running the model using all possible variations is unlikely to equal the results of running the model using “average” weather. Figure A.5 illustrates the differences in results from IMPACT when using variable monthly precipitation in Spain and when using the “average weather” assumption.

Figure A.5. Comparing variable and average weather in Spain (IMPACT)



Additionally, it should be noted that the IPSL and Hadley GCMs do not model some other aspects of climate change, such as rises in sea levels, that might be significant when assessing climate change impacts on agriculture located in coastal areas. This may result in an underestimation of the effects of climate change. On the other hand, because the models assume that climate effects will increase in a straight line, rather than rising slowly in the beginning, then climbing steeply, climate effects in the shorter run are likely to be overestimated.

This has consequences for the projections of adaptation costs. On the one hand, it is assumed that it is possible for autonomous adjustment processes to occur in a gradual manner: variability (such as droughts) is ignored. The absence of such climate variability would, other things being equal, suggest that the ability to adapt is overestimated in the model, and that actual transition costs could be larger than projected. On the other hand, the overestimation of short-term climate impacts may imply that there is more time to adapt to the effects of climate change than the climate models suggest, and thus transition costs could be overestimated, at least in the short run.

Annex B.

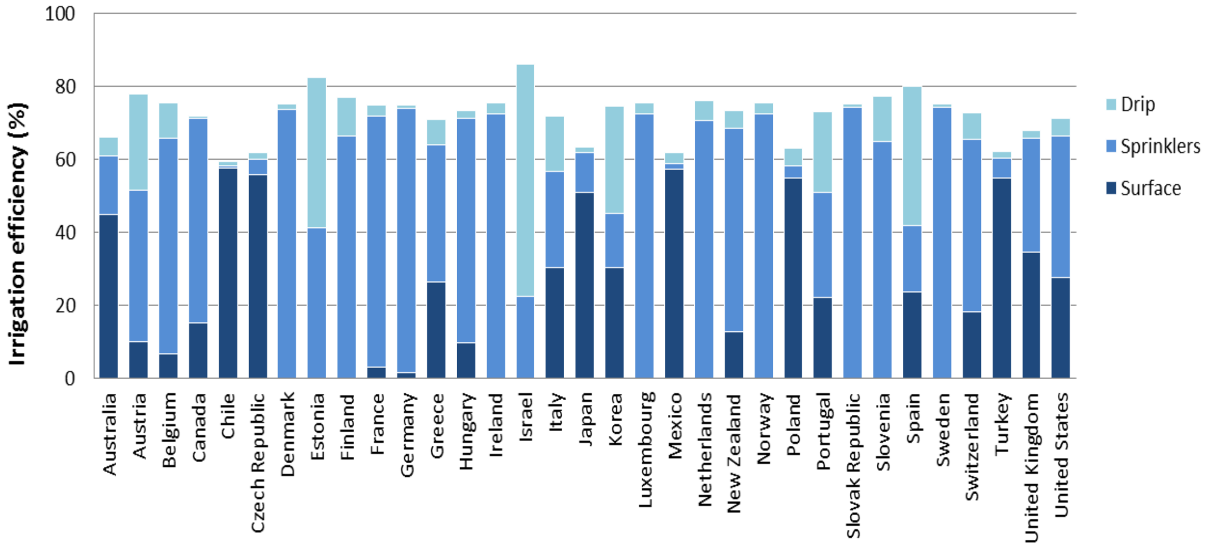
Description of the water management scenarios

Irrigation efficiency improvement

Some irrigation systems are inefficient in terms of how much water actually reaches 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 OECD countries, which means that about 40% of water is lost during transportation to the field. Sprinkler irrigation, where water is sprayed on crops via a pressurised system, increases 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 dripping pattern. Such systems increase the efficiency in water use to about 90%. Changing from one irrigation technology to a more efficient technology, or improving inefficient irrigation technology by, for instance, insulating or covering canals to reduce evapotranspiration, is a good way to prevent water loss.

Figure B.1 presents the average irrigation efficiency in each OECD country. The highest efficiency in irrigation water use (about 86%) is achieved in Israel; the lowest efficiency rate (about 61%) is found in Chile, Mexico and Turkey. The efficiency level is strongly related to the predominant type of irrigation system that is used in a country. In Israel, almost three-quarters of total irrigated land is equipped with highly efficient drip irrigation. Mexico and Chile are predominantly equipped with surface irrigation.

Figure B.1. Irrigation efficiency and share of irrigation technologies in OECD countries

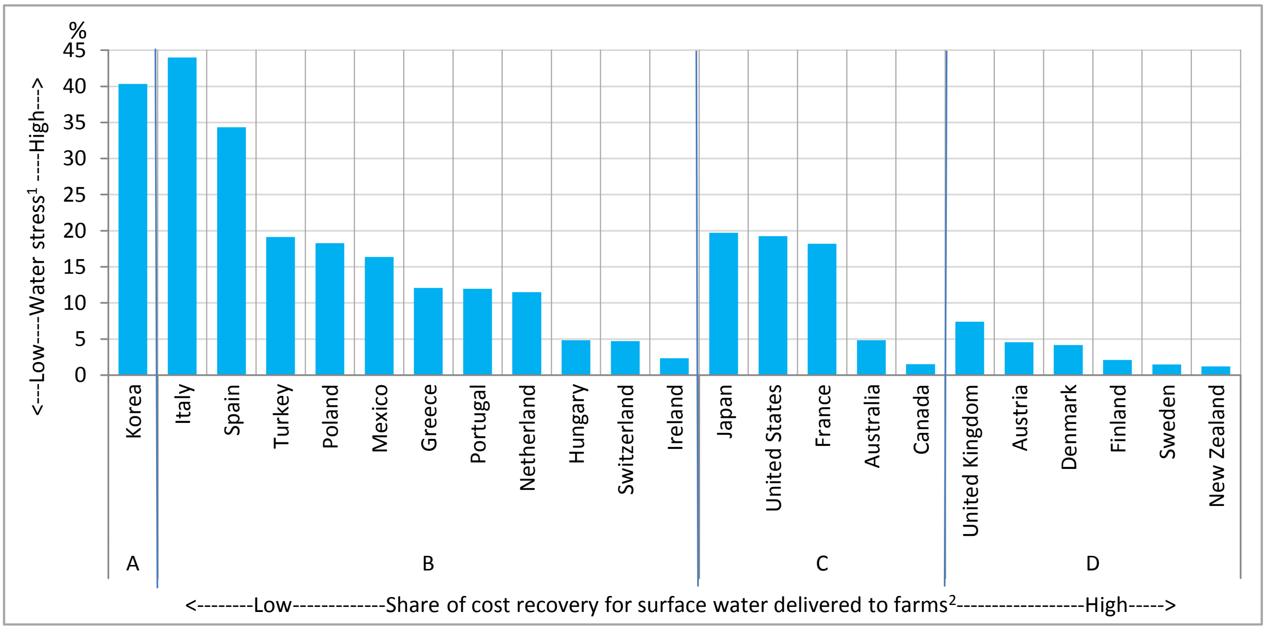


Source: Own compilation.

The use of efficient water technologies contributes 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 the periods 1990-92 and 2002-04, while in most cases the volume of agricultural production increased (OECD, 2010b).

The demand for water by the agricultural sector across OECD countries is almost constant; however, due to growing demand from other sectors, the pressure on water resources in some regions is increasing (OECD, 2013). This may induce water stress. Some states in the United States, such as California, as well as many Mediterranean countries, already battle with increasing water stress (OECD, 2010b). Figure B.2 provides more detail about the level of water stress in a selection of OECD countries. Although water stress by itself may have negative consequences for productivity, combined with a supporting set of policies it may stimulate more efficient water allocation and the adoption of sustainable water management techniques. However, OECD research (2010) shows that in many countries, farmers are only charged for the operation and maintenance portions of their water supply costs, with little recovery of the capital costs of water supply infrastructure. Therefore, it is important to ensure that the charges for water supplied to agriculture reflect the full supply costs.

Figure B.2. The extent of water stress and cost recovery for surface water delivered to farms across OECD countries in the late 2000s



Notes:

1. Water stress:

Water stress is defined as water withdrawals by all users (i.e. urban, industrial, power and agriculture) as a percentage share of annual water availability (i.e. quantity of water from precipitation net of evapotranspiration and inflowing rivers from neighbouring countries). The OECD uses the following thresholds for water stress: Low – below 10%; Moderate – between 10 and 20%; 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 OECD Environmental Compendium data 2006-2008 (www.oecd.org/environment).

Theoretically, the implementation of water efficient technologies contributes to a reduction in waters stress and, in general, to more sustainable resource use. In practice, however, in some places water savings technology increases water demand. In Pakistan, farmers who use efficient water technologies actually use the "saved" water to intensify their agricultural production and expand their irrigation area (Ahmad et al., 2013). A similar situation occurred in the state of Kansas in the United States: According to Pfeiffer and Lin (2013), the intended reduction in water use resulting from using more efficient irrigation technologies did not occur because farmers shifted their cropping patterns towards high-value, water-intensive crops. This suggests that in order to decrease 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).

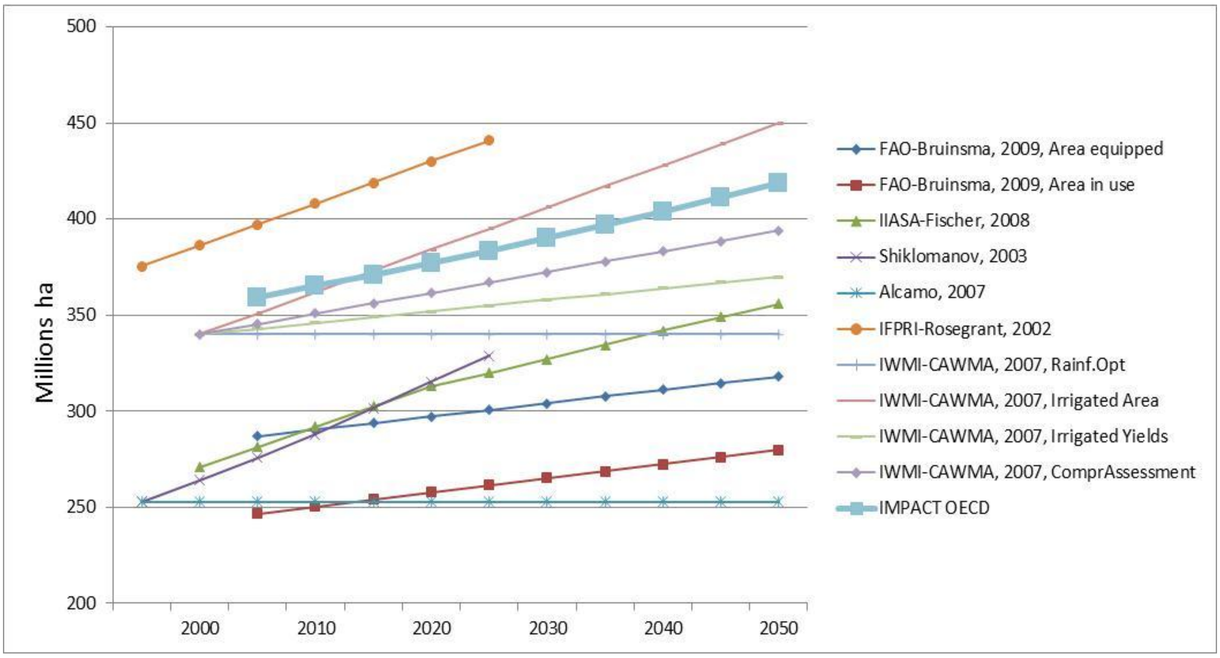
Another, unintended effect of using very efficient irrigation technologies is a reduction in ground water replenishment. While inefficient water systems "waste" water in terms of delivering less water to the plant, these systems also replenish groundwater reservoirs. OECD (2014b) discusses this effect in detail.

Irrigation expansion

Irrigation is often seen as a means to increase agricultural yields and to enhance the quality of crops. It is often described as a self-insurance tool against drought and is used to smooth farmers' incomes (Amigues et al., 2006; Foudi and Erdlenburch, 2011). Globally, around 360 million hectares is irrigated. The availability of water to irrigate agricultural land in the future will strongly depend on current and future precipitation, but also on future socio-economic developments that will determine water demand from other sectors. According to an OECD study (2013), major new irrigation infrastructure developments will be limited due to financial and physical restraints. Figure B.3 shows that many studies that examine (growing) water demand from other sectors assume that global irrigated areas will remain stable or only increase slightly. Most of the time, the increase is associated with irrigated areas in developing countries.

According to the *OECD Environmental Outlook to 2050* (OECD, 2012c), the total water supply in OECD countries may be lower in 2050 than in 2000, with the largest decrease in water availability occurring in the agricultural sector. It is assumed that the total irrigated area will remain constant but that irrigation efficiency will increase significantly. Based on recent observations (OECD, 2013), irrigated areas increased in the 1990s; however, in recent years a decrease in the area of irrigated land in OECD countries has been observed. Total demand for water in the rest of the world is expected to increase significantly. By 2050, agriculture may still be one of the major users of water, but the demand from other sectors such as electricity generation and manufacturing may increase a few times over. 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 drinking water.

Figure B.3. Projected global irrigated area



Source: Adapted from *Global Irrigation Water Demand Projections to 2050: An Analysis of Convergences and Divergences*, OECD, 2012b.

At the farm level, the empirical literature shows that farmers are sensitive to climate averages and variances and build their 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 in their income. Farmers with relatively stable income are less inclined to invest in irrigation (Koundouri et al., 2009; Foudi and Erdlenburch, 2011). This affects the degree to which farmers will adopt available technologies to maximise and smooth their own profits. Irrigation requires significant upfront investments and may be relatively labour intensive. Decisions as to 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 C.

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 targets developing countries, some modifications were necessary. The same method was applied to estimate the adaptation costs in both the public and private sectors. It is important to include private R&D in analyses because the growth rate in public agricultural R&D investments has slowed and there has been an increase in the rate of 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.[9] To calculate future expenditures for public agricultural R&D, the "*Government budget appropriations or outlays for RD*" in agriculture was used.[10] For the estimation of private expenditures, the "*Gross domestic expenditure on R-D by sector of performance and socio-economic objective in NABS2007*" was used. Private agricultural R&D expenditure is defined as R&D expenditures by private NPOs and business enterprises.[11] To estimate private expenditures on agricultural R&D in the United States, data from *Research Investments and Market Structure in the Food Processing, Agricultural Input, and Biofuel Industries Worldwide* (Fuglie et al., 2011, p. 9, Table 1.5) was used and converted into 2005 US dollars 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 a particular country or, where only one estimate was provided, the growth rates for the OECD. Additionally, where no information was provided for private sector R&D expenditures, the R&D expenditure ratio of private to public expenditures between 2001 and 2010 (0.554) was used.

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[9] The R&D data for Chile and Turkey are unavailable; therefore, these two countries are omitted in our R&D cost estimation.

[10] Available at http://dotstat.oecd.org/Index.aspx?DataSetCode=GERD_OBJECTIVE_NABS2007: Accessed on 5 March 2013.

[11] 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 would seem to be suitable data to use as public R&D expenditure. However, the data contains many missing values compared with the aforementioned dataset.

First, following the World Bank (2010) methodology, the baseline R&D expenditures in 2050 assuming no climate change impacts were estimated based on equation (1).

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

where ARn is the annual expenditures on agricultural R&D in the years 2011 to 2050, and g_a is the historical growth multiplier in Table C.1 g_h represents the historical growth rates by countries.

Table C.1. Assumed multipliers of historic growth rates (g_a) of agricultural R&D

Agricultural R&D	2011-2020	2021-2030	2031-2040	2040-2050
ga (%)	8	7	6	5

Source: World Bank (2010).

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

$$AR_{senario} = \left[- \frac{0.5\left(\frac{Yld_{2050}^{Senario} - Yld_{2050}^{Baceline}}{Yld_{2050}^{Baceline}}\right)}{\varepsilon_{Research}^{Yield}} \right] AR_{baseline} \quad (2)$$

where Yld_{2050}^{y} is the average of cereal yields in each sector and $\left(\varepsilon_{Research}^{Yield}\right)$ is the yield elasticity with respect to R&D expenditures in each region (Table C.2).

Table C.2. The yield elasticity with respect to R&D expenditures

Regions	Elasticity	Source
Japan and Korea	0.14	Pratt & Fan (2010)
United States, Canada, and Israel	0.187	Alston (2010)
Europe	0.22	Barnes (2002), Thirtle et al. (2008)
Australia and New Zealand	0.22	Mullen (2007)
Mexico	0.296	World Bank (2010)

Source: compiled by authors.

It should be noted that elasticities used in this analysis are different from those used by the 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 impacts of climate change are the same.

Methodology to calculate irrigation investment costs

The World Bank methodology is applied to estimate the annual investment costs 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 each 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):

$$BE_1 = \frac{BC_0}{TC_1} \qquad (1)$$

Subscript "0" denotes the base scenario and "1" denotes the alternate irrigation investment scenario. Total irrigation water consumption is calculated using the share of the total irrigated area in 2050 with the more efficient irrigation technology (*X*), namely sprinkler or drip technology:

$$TC_1 = BC_0 \cdot \frac{1-X}{BE_0} + BC_0 \cdot \frac{X}{E_1} \qquad (2)$$

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

$$X = \frac{(BE_0 / BE_1) - 1}{(BE_0 / E_1) - 1} \qquad (3)$$

The irrigation efficiency investment costs (*IEinvt*) consist of three components. The first is the cost related to changing to the more efficient irrigation efficiency per hectare (*IE cost*). The second is the total irrigated area (*AI*) in hectares in 2050. The third component is the share of total irrigated area in 2050 equipped with the more efficient irrigation technology. Together these will give the total investment costs for a country:

$$IEinvt = IE\cos t \cdot AI \cdot X \qquad (4)$$

The investment cost is only relevant when BE_1 is higher than BE_0; if this is not the case, the investment costs are not calculated. The target efficiency rate is set at 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 rates of surface, sprinkler and drip technology are* 60%, 75% and 90%, respectively (http://www.fao.org/docrep/t7202e/t7202e08.htm). The two exceptions are Portugal, which has an efficiency rate of 80% for drip irrigation (www.iwra.org/congress/2008/resource/authors/abs878_article.pdf), and Spain, which has efficiency rates of 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 at 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 irrigation efficiency in Japan, different management technologies may be used, including more precise timing of irrigation. This is incorporated by setting BE_1 to 65%, which represents a 3% increase in irrigation efficiency for Japan.

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

The cost of the irrigation technology per hectare

Country	Costs of the technologies	Source
European countries	USD 1 700 for surface USD 2 800 for sprinkler USD 3 950 for drip	FAOSTAT ftp://ftp.fao.org/docrep/fao/010/a1336e/a1336e.pdf
Australia and New Zealand	USD 2 274 for sprinkler USD 5 000 for drip	www.nwc.gov.au/__data/assets/pdf_file/0013/10921/Waterlines_53_PDF_Fellowship-_Technological_change_in_the_irrigation_industry.pdf
Canada and the United States	USD 1 290 for surface USD 2 921 for sprinkler USD 4 438 for drip	www.ksre.ksu.edu/bookstore/pubs/mf836.pdf
Israel	USD 202 for drip	www.askgillevy.com/news_details.php?id=9
Poland	USD 1 649 for sprinkler USD 3 950 for drip	www.infraeco.pl/pl/art/a_15605.htm?plik=637
Chile, Korea, Japan and Mexico	USD 2 730 for sprinkler USD 3 927 for drip	Data not available, the average costs of the other OECD countries is used

Share of technology used

Country	Source
Australia	Land and Water Australia http://lwa.gov.au/files/products/national-program-sustainable-irrigation/pn22088/pn22088.pdf
Austria, Belgium, Denmark, Netherlands, Norway	Eurostat http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do;jsessionid=9ea7d07e30d67044a33a8f1b4d088258bb0df1bedb2d.e34MbxeSahmMa40LbNiMbxaMbNqOe0
Canada, Finland, France, Japan, Korea, Mexico, New Zealand, Switzerland, Turkey, United Kingdom	FAO www.fao.org/nr/water/aquastat/data/query/index.html?lang=f
Chile, Czech Republic, Estonia, Germany, Hungary, Israel, Italy, Poland, Slovak Republic, Spain	ICID www.icid.org/annualreport.html
Portugal	National Statistical Institute – 2009 Agricultural Census
Greece	CIHEAM http://om.ciheam.org/om/pdf/b52/05002251.pdf
Ireland, Luxembourg, Sweden	European Commission http://ec.europa.eu/environment/water/quantity/pdf/water_saving_1.pdf
Slovenia	Statistical office of the Republic of Slovenia www.stat.si/eng/novica_prikazi.aspx?ID=5515
United States	USDA www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/fris08_1_04.pdf
Iceland	Data not available