Policy Research Working Paper 8744

Beyond the Gap
How Countries Can Afford the Infrastructure They Need While Protecting the Planet

Background Paper

Investment Needs for Irrigation Infrastructure along Different Socioeconomic Pathways

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Abstract

This paper conducts an assessment of the global costs for expanding, upgrading, and improving irrigation infrastructure in developing countries, along different future scenarios toward 2050. It uses the GLobal BIOsphere Management Model, a partial equilibrium model of the global agricultural and forestry sectors. It examines the impacts of irrigation expansion on the agriculture and food system, from the perspective of different Sustainable Development Goals, in particular food security (goal 2), land use change and biodiversity (goal 15), greenhouse gas emissions (goal 13), and sustainable water use (goal 6). It finds that irrigation support policies improve food security globally and can reduce the burden on land by limiting expansion of cropland area. However, the effectiveness of irrigation to achieve a larger set of goals depends on the regional context. In South Asia and the Middle East and North Africa, the expansion of irrigation increases unsustainable water extraction practices. A sensitivity analysis is conducted to evaluate the uncertainty of the infrastructure costs and impacts under different socioeconomic developments, levels of radiative forcing and climate change scenarios, dietary patterns, trade openness, and efficiencies of irrigation systems. The findings indicate that irrigation systems could play an important role in adaptation to the most adverse climate change; however, increased water scarcity may also limit adaptation potentials.

This paper was commissioned by the World Bank Group's Chief Economist office for Sustainable Development Practice Group and is a background paper for the World Bank Group's report: *"Beyond the Gap: How Countries Can Afford the Infrastructure They Need While Protecting the Planet."* It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/research. The authors may be contacted at palazzo@iiasa.ac.at.

Produced by the Research Support Team

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Keywords: agriculture, irrigation, infrastructure investment, food security

JEL: Q10: Agriculture

Q15: Land Ownership and Tenure; Land Reform; Land Use; Irrigation; Agriculture and Environment

Q25: Renewable Resources and Conservation: Water

H54: National Government Expenditures and Related Policies: Infrastructures; Other Public Investment and Capital Stock

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Supplementary information for this working paper can be found here: http://pure.iiasa.ac.at/id/eprint/15748/

Regional Definitions

AFR	Sub-Saharan Africa Region
	Includes: Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cabo Verde, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Congo Republic, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, the Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Eswatini, Tanzania, Togo, Uganda, Zambia, Zimbabwe
EAP	East Asia and the Pacific Region
	Includes: Brunei Darussalam, Cambodia, China, Fiji Islands, French Polynesia, Indonesia, People's Democratic Republic of Korea, Republic of Korea, Lao People's Democratic Republic, Malaysia, Mongolia, Myanmar, New Caledonia, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, Thailand, Timor-Leste, Vanuatu, Vietnam
ECA	Europe and Central Asia Region
	Includes: Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Macedonia, Moldova Republic, Montenegro, Poland, Romania, Russian Federation, Serbia, Slovak Republic, Slovenia, Tajikistan, Turkey, Turkmenistan, Ukraine, Uzbekistan
LCR	Latin American and Caribbean Region
	Includes: Argentina, Bahamas, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Falkland Islands, French Guiana, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad Tobago, Uruguay, República Bolivariana de Venezuela
MNA	Middle East and North Africa
	Includes: Algeria, Bahrain, Arab Republic of Egypt, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, West Bank and Gaza, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates, Western Sahara, Republic of Yemen
SAR	South Asia Region
	Includes: Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka
NAM	North America Region
	Includes: United States, Puerto Rico, and Canada
ADP	Pacific and Asian Developed Region
	Includes: Australia, Japan, New Zealand
EC	European Community Region
	Includes: Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Greenland, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom

Abbreviations and Acronyms

AFOLU	Agriculture, Forestry, and Other Land Use
AQUASTAT	global water information system of the FAO; developed by the FAO Land and Water Division
BRICS	association of five emerging countries, Brazil, Russia, India, China and South Africa
CGIAR	Global partnership of 15 organizations engaged in research dedicated to reducing rural poverty, increasing food security, improving human health and nutrition, and ensuring sustainable management of natural resources
CMIP5	Coupled Model Intercomparison Project Phase 5
CO2	Carbon Dioxide
CWATM	Community Water Model; open source hydrological model developed at IIASA
EFR	Environmental Flow Requirement
EPIC	Environmental Policy Integrated Climate Model; globally gridded crop model
FAO	Food and Agriculture Organization of the United Nations
GCM	General Circulation Model
GDP	Gross Domestic Product
GFDL/GFDL-ESM2M	General Circulation Model of NOAA Geophysical Fluid Dynamics Laboratory
GGCM	Globally gridded crop model
GHG	Greenhouse gas
GLOBIOM	GLobal BIOsphere Management Model; developed at IIASA
HadGEM/Had GEM2-ES	General Circulation Model of Met Office Hadley Centre
IIASA	International Institute for Applied Systems Analysis
IPSL/IPSL-CM5A-LR	General Circulation Model of Institut Pierre-Simon Laplace
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
LPJml	Lund-Potsdam-Jena managed land model; dynamic vegetation model developed at the Potsdam Institute for Climate Impact Research
LUC	Land use change
LULUCF	land use, land use change, and forestry
MER	Market Exchange Rate
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact; energy model developed at IIASA
MIROC/MIROC-ESM-CH	General Circulation Model for Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
NEPAD	New Partnership for Africa's Development
NOR/NorESM1-M	General Circulation Model for Norwegian Climate Centre
PCR-GLOBWB	PCRaster GLOBal Water Balance model; hydrological model developed at Utrecht University
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
SSP	Shared Socioeconomic Pathway
USAID	United States Agency for International Development
WAE	Water application efficiency
WFaS	Water Futures and Solutions Project

1. Introduction

Agriculture productivity can play an important role to improve food security and achieve some of the sustainable development goals (SDGs). Intensification through irrigation is often mentioned as a good option to make progress towards achieving the SDG 2 goal ("End hunger, achieve food security and improved nutrition and promote sustainable agriculture") and to reduce the pressure on land (SDG 15 "…sustainable use of terrestrial ecosystems"). Expansion of irrigation is also considered an adaptation option in the face of climate change, expected to strongly affect rainfed agriculture (Leclère et al., 2014a; Müller et al., 2011; Roudier et al., 2011). However, in water stressed regions, an increased role for irrigation poses challenges for water availability (SDG 6 "Ensure availability and sustainable management of water and sanitation for all"). Transforming traditional rainfed systems or upgrading water inefficient irrigation systems into productive irrigation systems will require investments that may be beyond the economic means of farmers in vulnerable regions.

In this paper we quantify the impacts and costs of investment strategies for maintaining, upgrading and expanding irrigated agriculture in developing countries, along different future scenarios towards 2050. For this purpose, we model the supply and demand of agricultural products at a high spatial resolution in an integrated approach that considers the impacts of global change (socioeconomic and climatic) on food, feed, and fiber markets using a global economic and land use model GLOBIOM (Havlik et al., 2014). We examine the impacts of related irrigation expansion on the agriculture and food system, in the perspective of different Sustainable Development Goals (SDGs), in particular food security (SDG2), land use change and biodiversity (SDG15), greenhouse gas emissions (SDG13) and water withdrawals (SDG6).

Our approach models the conditions and investment required to transform rainfed cropland into highly productive and efficient irrigated cropland, taking into account the biophysical availability of water, the growing competition for water from other sectors (domestic, energy and industry) as well as the impacts that upgraded and expanded irrigation systems have on regional crop production, land use change and emissions, as well as food security and water availability. We implement the investment and support for irrigation as different levels of subsidy on the large-scale capital costs and on-farm capital costs. We also restrict the water used for irrigation to the quantity that is physically available after domestic and industrial demand has been satisfied. Partial subsidies for the capital costs to build large-scale dams and water delivery systems are assumed to be publically funded in our investment support scenarios. Our approach considers four categories of irrigation investment costs– costs to expand irrigated area, costs to upgrade irrigation systems from less efficient to more efficient systems, costs to improve the overall efficiency of a less efficient system, and depreciation costs.

We look at two different levels of ambition for irrigation development, where irrigation expansion and upgrade investment in developing regions are supported by public investments: a moderate public support scenario (*Invest*) on the large-scale capital costs leading to 32% more irrigated area by 2050 in developing countries; and a high public support (*MaxInvest*) scenario where large-scale and on-farm capital costs are heavily subsidized, enabling a 70% increase in irrigated area. Such deployment would require public investment costs of about $26 billion to $50 billion per year, in constant 2000 US dollars. These scenarios are compared to a counterfactual where no more investment in irrigation would take place. Our scenario analysis is complemented by a comprehensive uncertainty assessment investigating the roles of macroeconomic development, climate change, future diets, water efficiency and trade policies.

Our results show that ambitious support and investment to improve, upgrade and expand irrigated areas can have an impact on improving food security and reducing the burden on land. In our most ambitious scenario, *MaxInvest*, 154 million hectares could be added which corresponds to a 60% increase in irrigated areas in developing countries from 2010, and the use of about 73% of the irrigable area potential in those regions (FAO, 2017). A more easily achievable scenario, *Invest*, would expand irrigated land by 71 million hectares (+32%) and make notable improvements in food security in a number of regions but have less impact on reaching the climate and land SDGs than our ambitious support scenario.

We observe that climate change scenarios and trade policies are the most likely to affect irrigation strategies and their impacts across the SDGs. Irrigation appears as a key adaptation mechanism in regions with sufficient water supply, but climate change also limits in some areas the overall water availability and potential for irrigation expansion. In the case of trade, restrictions lead to irrigation expansion for domestic production of food in South Asia and Middle East and North Africa, in case of exchange restrictions. On the contrary, more intensive trade favors expansion of irrigated area in Latin America and the Caribbean where a share of food needs can be relocalized. Investments into increased water use efficiency is also found to lead to mixed outcomes, with higher food production levels to the benefit of food security, but limited water savings due to the rebound effect of production.

According to our results, achieving ambitious expansion of irrigation and increase in irrigated cropland productivity in developing countries would cost $50 billion per year over the next 40 years -- decomposing in $16 billion in building new irrigation infrastructure (i.e. providing access to water for irrigation and equipping rainfed cropland with irrigation equipment), $32.7 billion in depreciation costs, $0.6 billion in upgrading irrigation systems to more efficient systems (i.e. moving from gravity-based irrigation systems to sprinkler or drip), and $0.2 billion in general efficiency improvements of irrigation systems (i.e. improving the water application efficiency of gravity-based irrigation systems). Approximately a quarter of the expansion costs would occur in Sub-Saharan Africa, 32% in East Asia and the Pacific, 5% in Middle East and North Africa, and 17% in Latin America and the Caribbean, 14% in South Asia, and 10% in Europe and Central Asia.

Multiple benefits would accrue from this irrigation increase, in terms of efficiency of irrigation systems, food availability, and land sparing. However, our results also show that, for some regions, development of irrigation is by no means a panacea when confronted to the SDGs, and careful planning is needed to secure the benefits from such large investments. Unsurprisingly, investments in irrigation would lead to improvement in food availability and hence contribute to improved food security in all the considered regions (SDG2). However, the effectiveness and efficiency in achieving this goal through expanded irrigation differs substantially across regions; an investment of $4.3 billion per year would improve the food availability in Sub-Saharan Africa by less than 1% by 2050 while an investment of $6.8 billion per year would improve the food availability in South Asia by 2.5% by 2050.

The results are even more ambiguous in terms of environmental impacts. Irrigation expansion is expected to play a land sparing role and ease protection of forests and natural land for biodiversity conservation (SDG15). While in Eastern Europe and Central Asia and in Latin America and Caribbean irrigation expansion leads to reduction in cropland area expansion with a positive effect on natural habitat protection, in Eastern Asia and Pacific and in South Asia, expansion of irrigation would lead to further expansion of cropland at the expense of natural habitats. The effect on GHG emissions (SDG13) is in most cases negative because of emissions from additional agricultural production, and in many regions also from additional conversion of natural areas including forests. Finally, the irrigation infrastructure expansion leads to substantial additional water withdrawals and in Europe and Central Asia, South Asia, and Middle East and North Africa leading to a competition with environmental water flows requirement which is our proxy used for the sustainability of water withdrawals (SDG6), though the local impacts in other regions such as East Asia and Pacific may be significant.

Consideration of these multiple trade-offs with SDGs helps to determine the regions where investments could be targeted with limited adverse impacts. According to our findings (Table 1), the most relevant regions for such large-scale irrigation investments would be Europe and Central Asia, Middle East and North Africa, and South Asia where substantial benefits are to be expected with limited negative effects.

Table 1. Summary of the difference in impacts by indicator for Investment Scenarios relative to ZeroInvest in 2050 with color-coded SDG scoring

	Irrig. Area	Investment Cost	Crop prices	Food availability	GHG AFOLU	Cropland	Other Nat Land	Forest	Env. Flow Requirem ent
	Mha	\$ Billion[1]/ year	% change	kcal/cap/ day	$MtCO_2eq$	Mha	Mha	Mha	% of EFRs at risk[2]
Invest									
AFR	8.8	3.7	-2.0	9.9	-4.6	1.5	0.1	-0.3	0.7
EAP	36.7	6.4	-2.3	13.5	68.6	1.5	-0.8	-1.2	0.8
ECA	5.4	0.8	-0.5	2.3	5.1	-0.7	0.6	0.0	0.4
LCR	12.4	2.0	-0.5	7.3	7.9	-4.0	2.0	0.4	0.3
MNA	4.4	1.1	-5.1	18.0	8.3	1.0	-0.7	0.0	7.1
SAR	38.2	3.4	-2.9	51.0	72.4	3.2	-2.2	0.0	6.7
WLD	104.3	17.2	-1.8	20.2	143.7	1.0	0.4	-1.1	0.8
MaxInvest									
AFR	22.7	10.1	-2.2	7.7	-10.9	-1.3	2.3	-0.5	2.0
EAP	49.4	11.3	-3.3	34.9	67.9	1.6	-1.9	-1.1	2.0
ECA	18.5	4.7	-1.5	8.0	7.0	-3.7	2.8	0.0	2.6
LCR	43.5	8.0	-7.3	54.1	99.0	-5.4	8.1	-4.9	1.6
MNA	5.9	1.7	-6.5	19.7	6.9	1.0	-0.7	0.0	7.4
SAR	49.6	4.8	-5.1	71.0	71.5	5.6	-3.1	0.0	12.2
WLD	187.7	40.3	-3.8	34.2	221.4	-4.9	10.1	-6.5	2.1

This working paper is structured as follows. Section 2 describes the methods we used for this analysis including the modeling framework, the irrigation investment scenarios, and the sensitivity analysis. Section 3 presents the investment needs and the composition of irrigation systems under the scenarios. Section 4 presents the impacts of the irrigation investments on the SDGs. Section 5 provides the sensitivity analysis. Finally, Section 6 concludes the working paper.

Additional results and figures are available in the supplementary information[3] with more details on the modeling framework, regional results, and sensitivity analysis. Figures from the supplementary information are referenced in this paper with the "SI" prefix.

[1] Constant 2000 dollars.

[2] The total volume of environmental flow requirement (EFR) at risk to become unsustainable is calculated first by identifying pixels in which at least one month of the volume of surface water withdrawals by irrigation are in excess of the volume that should be left for the environment and then calculating the total volume of EFR in the unsustainable pixels over the entire growing period. The total volume of EFRs for unsustainable pixels is then compared to the total volume of EFRs for the region to calculate the share.

[3] http://pure.iiasa.ac.at/id/eprint/15748/

2. Methods

2.1. Modeling framework

GLOBIOM is a partial equilibrium model representing land-use based activities: agriculture, forestry and bioenergy sectors. The model uses a bottom-up approach to crop, livestock, and forestry production based on detailed biophysical and cost information at the gridcell level, while demand for food and fiber are represented at the level of 30 economic regions. Markets in GLOBIOM consider bilateral trade policies and barriers as well as transportation costs (Mosnier et al., 2014). The bottom-up modeling approach of the model considers the biophysical environment of production under multiple management systems for 18 globally produced crop products at a gridcell-level for four crop management systems: subsistence farming, low input rainfed, high input rainfed, and high input irrigated (Leclère et al., 2014b; von Lampe et al., 2014a). GLOBIOM dynamically models the use of cropland, pasture/grassland, managed and unmanaged forest, and other natural vegetation based on the availability of land and water and the relative profitability of each land sector given land rents and irrigation water costs and nonlinear conversion costs (Havlík et al., 2011b; Robinson et al., 2015, 2014; Schmitz et al., 2014).

GLOBIOM uses the globally gridded simulated crop yields and resource requirements (fertilizer, water for irrigation) from EPIC (Balkovič et al., 2013). The water demanded for irrigation is sourced by surface and groundwater and all irrigated areas are constrained to the water that is physically available after use for domestic and industrial purposes (Palazzo et al., 2018, 2017, Pastor et al., 2016, 2014). Section 1 of the supplementary information provides a more detailed description of the representation of irrigation as a crop production system within the modeling framework.

2.2. Scenario description

We developed and implemented several irrigation support scenarios to examine the impacts of investments in irrigation and applied the scenarios in GLBOIOM. In our scenarios, we implement the investment and support for irrigation as different levels of subsidy on the large-scale capital costs and on-farm capital costs. Table 2 provides an overview of components that make up the full cost of irrigation based on Rogers et al.'s (1998) conceptual overview of costing water for irrigation. Partial subsidies for the capital costs to build large-scale dams and water delivery systems are assumed to be publically funded in our investment support scenarios.

Subsidies for capital costs from government agencies or basin authorities are still common in many developed countries (including Canada, Australia, Greece, France, Italy, and Spain) (See Table 1 in Toan, 2016). In many developing countries such as India, Pakistan, and China, all capital costs and part of the operation and maintenance costs are subsidized by state agencies and water user organizations (Toan, 2016). While Turral et al. (2010) broadly define public investment in irrigation as expenditures that create an enabling environment for producing economic output and include "irrigation and drainage development, modernization, institutional reform, improved governance, capacity building, management improvement, creation of farmer organizations, and regulatory oversight, as well as farmers' investment in joint facilities, wells, and on-farm water storage and irrigation equipment" (p 553). While many of these activities and expenditures have an economic cost, some are beyond the scope of what can be represented in an economic land use modeling framework and are not considered in our approach.

Additionally, we assume that a portion of the costs from the public sector include training as it is an essential component to effectively use and maintain irrigation systems and is often publicly funded, as seen in some Sub-Saharan Africa case studies (Van Koppen et al., 2005). Subsidizing the cost of water for irrigation has become common practice in developed regions like Europe and the US as a means to encourage agricultural development, though many of these policies are currently being reformed due to their environmental impacts (such as over-extraction and water pollution, see Wichelns, 2010).

ZeroInvest

ZeroInvest is a scenario where there is no new investment in irrigation and therefore no expansion of irrigated areas beyond 2010 levels in developing regions. There are no investments to improve the water application efficiency of existing irrigation systems. Water used for irrigation is limited to the quantity that is physically available after domestic and industrial demand has been satisfied.

ZeroInvest is used as a reference scenario but not a policy scenario.

Invest

Invest is a *moderate public support* scenario where the irrigation equipment investment costs needed to expand irrigated areas or upgrade existing areas to more efficient irrigation systems in developing regions are supported by public investments, leading to 32% more irrigated area by 2050 in developing regions. Farmers are responsible for the operations and maintenance of the systems, which have been included in the model as production costs. The price of water that farmers face for irrigation use reflects the on-farm capital costs to utilize water as well as the relative scarcity of water due to the increasing demand for water for other sectors. *Invest* reflects a mixed-cost sharing policy that is similar to the one used in the Fadama Project in Nigeria in which a portion of the parts and materials were subsidized (Foster and Briceno-Garmendia, 2009).

In *Invest* the underlying improvement in the efficiency of water application, “more crop per drop” improves by 1.5% each decade. Efficiency can be achieved through upgrades or conversion of existing flood/gravity irrigation systems to more drip and sprinkler systems or by improving the overall efficiency of flooding/gravity irrigation systems. Water used by irrigation is limited to the remaining portion of physically available water at the pixel level after domestic and industrial demand has been satisfied.

MaxInvest

MaxInvest is a *high public support* scenario where ambitious investment in expanding and upgrading irrigated areas in developing regions are supported by public investment, leading to an increase of irrigated area by almost 70% by 2050 in developing regions. As with *Invest*, farmers are responsible for the operations and maintenance of the systems, which have been included in the model as production costs. Additionally, the price of water that farmers face is subjected to scarcity impacts although some of the on-farm capital costs are subsidized making the per unit price of water less expensive. The main difference between the *Invest* and *MaxInvest* scenarios is that *MaxInvest* reflects a policy where priority is given to increasing the accessibility of water by fully subsidizing it.

In *MaxInvest*, the underlying improvement in the efficiency of water application, “more crop per drop” improves by 3.0% each decade. Efficiency can be achieved through upgrades or conversion of existing flood/gravity irrigation systems to more drip and sprinkler systems or by improving the overall efficiency of flooding/gravity irrigation systems. Water used for irrigation is limited to the quantity that is physically available after domestic and industrial demands have been satisfied.

Regional MaxInvest

Regional *MaxInvest* scenarios correspond to the *MaxInvest* scenario but investments are implemented in only one World Bank region. These scenarios are important to disentangle the interaction effects between regions in the *MaxInvest* scenario. Water used for irrigation is limited to the quantity that is physically available after domestic and industrial demand has been satisfied.

Table 2. Overview of the types of costs associated with irrigation as defined by Rogers et al. (1998) and the subsidy assumptions by investment scenario

<table>
<tr><th>Type of irrigation cost</th><th>Reference</th><th colspan="2">Responsible for costs in Invest</th><th colspan="2">Responsible for costs in MaxInvest</th></tr>
<tr><td>1.Operation and maintenance</td><td></td><td colspan="2" rowspan="4">Producer
(within GLOBIOM as production cost)</td><td colspan="2" rowspan="4">Producer
(within GLOBIOM as production cost)</td></tr>
<tr><td>a. Energy (gasoline, diesel, electricity, animal power, or human power)</td><td>Sauer et al. (2010), FAO (2016)</td></tr>
<tr><td>b. Labor</td><td>FAO (2008), Sauer et al. (2010), FAO (2016)</td></tr>
<tr><td>c. Routine maintenance and wear-and-tear</td><td>FAO (2008)</td></tr>
<tr><td>2. Capital costs</td><td></td><td>Large scale infrastructure</td><td>On-farm</td><td>Large scale infrastructure</td><td>On-farm</td></tr>
<tr><td>a. Engineering, engineering management</td><td>Inocencio et al. (2005), Inocencio et al. (2007), FAO (2016)</td><td rowspan="5">Public Sector
(in ex-post investment cost calculation as expansion costs, upgrade costs, and efficiency costs)</td><td rowspan="6">Producer
(within GLOBIOM as production cost and land conversion cost)</td><td colspan="2" rowspan="5">Public Sector
(in ex-post investment cost calculation as expansion costs, upgrade costs, and efficiency costs)</td></tr>
<tr><td>b. Parts and material</td><td>Inocencio et al. (2005), Inocencio et al. (2007), FAO (2008), FAO (2016), Rosegrant et al. (2017)</td></tr>
<tr><td>c. Interest and finance costs</td><td>Inocencio et al. (2005), Inocencio et al. (2007), FAO (2008)</td></tr>
<tr><td>d. Training, technical assistance, institutional development, capacity strengthening</td><td>Inocencio et al. (2005), Inocencio et al. (2007), FAO (2008), Rosegrant et al. (2017)</td></tr>
<tr><td>e .Administrative costs</td><td>Inocencio et al. (2005), Inocencio et al. (2007), FAO (2008)</td></tr>
<tr><td>f. Depreciation</td><td>Schmidhuber et al. (2009)</td><td>Public Sector
(in ex-post investment cost calculation as depreciation)</td><td colspan="2">Public Sector
(in ex-post investment cost calculation as depreciation)</td></tr>
<tr><td>3. Resource costs</td><td></td><td colspan="2" rowspan="3">Producer
(within GLOBIOM as the water price)</td><td colspan="2" rowspan="3">Producer
(within GLOBIOM as water price)</td></tr>
<tr><td>a. Opportunity costs of alternative water uses</td><td>Toan (2016)</td></tr>
<tr><td>b. Taxes, licenses, and government levied resource fees</td><td>Van Koppen et al. (2005)</td></tr>
<tr><td>4. Environmental costs</td><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>a. Environmental damages</td><td>Toan (2016)</td><td colspan="2">Quantified as a share of agricultural water use that unsustainable but not modeled with a monetary value</td><td colspan="2">Quantified as a share of agricultural water use that unsustainable but not modeled with a monetary value</td></tr>
</table>

2.3. Sensitivity analysis

The investment support scenarios described above are implemented under central assumptions derived from the Shared Socioeconomic Pathway (SSP) 2: Middle of the Road (Fricko et al., 2017). In SSP2 the global population reaches 9.2 billion people (KC and Lutz, 2017) and global average GDP per capita doubles to around $16,000 (Dellink et al., 2017). We estimate crop and livestock productivity over the time period using an econometric estimate of the relationship between crop yields and GDP per capita assumptions of SSP2 (Fricko et al., 2017; Herrero et al., 2014).

The main scenarios of investment are complemented by some sensitivity analysis scenarios where some key assumptions and drivers from the SSP2 baseline are varied, to test their influence on the irrigation policy impacts. Table 3 provides an overview of the types of modeling assumptions we varied in the sensitivity analysis and a description of the alternative assumptions used. Section 5 provides the more detailed examination of the impacts of alternative assumptions for the sensitivity analysis on irrigation investments and impact of irrigation investments on the agriculture development, food security and land use change. First, we test the impact of irrigation investments under completely different socioeconomic pathways (SSPs). Our analysis considers SSP1, “Sustainability”, and SSP3, “Regional Rivalry” where the development of population and economic growth, speed of technological change in agriculture, dietary preferences and food waste management, as well as degree of globalization of agricultural commodity markets differ from the baseline (SSP2). We pay particular attention to the irrigation development storylines and the projections for water demand from domestic and industrial uses developed for the SSPs from Water Futures and Solutions Initiative (Wada et al., 2016) and Hanasaki et al. (2013).

The socioeconomic pathway SSP1 provides an alternative dietary preference scenario which moderates overconsumption and aims to reduce of the share of red meat in the diets compared to the diet preferences in the baseline (SSP2). Two additional diet scenarios are also modeled– healthy diet and healthy sustainable diet. The Healthy Diet scenario modifies current diets to set them strictly in line with the World Health Organization dietary recommendations and the Healthy Sustainable Diet scenario considers the land and water resource requirements of food items.

We evaluate the impacts of climate change using spatially explicit impacts on crop yields, irrigation water requirements which were calculated by the crop growth model EPIC (Balkovič et al., 2013) under the representative concentration pathway 2.6 and 8.5 for five global climate models (GCMs) and coupled to GLOBIOM. Additionally, the water available for irrigation is determined by the globally gridded monthly surface water availability and environmental flows is modeled by LPJmL (Palazzo et al., 2018, 2017, Pastor et al., 2016, 2014).

Over the time period, our baseline assumption is that the efficiency of irrigation systems (water application efficiency) moderately increases. We model two alternative specifications: a high water application efficiency for irrigation systems scenario with rapidly increasing irrigation water application efficiency through substitution of the inefficient systems by sprinkler and drip, and a low water application efficiency scenario with stagnating water use efficiency.

Finally, we analyze the effects of more integrated international markets (open trade) and more regionalized markets (restricted trade) and their role in irrigation investment needs.

Additionally, we combined various parameters and assumptions of the uncertainty scenarios described above to form more extreme scenarios. The goal of these “extreme scenarios” is to identify the smallest and largest expansion of irrigated areas as well as the least and greatest irrigation investment costs that would be required for those areas. The details of the modeling setup and results from the extreme scenarios appear in Section 4 of the supplementary information.

Table 3. Types of assumptions and drivers varied in the sensitivity analysis

Type of modeling assumption	Change from SSP2 assumptions
socioeconomic pathways (SSP)	SSP1 Sustainability SSP3 Regional Rivalry
dietary patterns	Healthy Diets Healthy and Sustainable Diets
climate change impact magnitude	HadGEM2-ES IPSL-CM5A-LR GFDL-ESM2M MIROC-ESM-CHEM NorESM1-M HadGEM without CO_2 fertilization
water application efficiency	High water application efficiency for irrigation Low water application efficiency for irrigation
trade openness	Open trade Restricted Trade

3. Investment needs for irrigation and impacts on irrigation systems

3.1. Irrigation investment costs

We estimate the investment costs required to expand irrigated areas, to upgrade irrigation systems from less efficient to more efficient systems, and to improve the overall efficiency of irrigation systems. Expansion of irrigated areas involves a transformation of rainfed cropland area or the conversion from forested or other natural lands. Upgrade improvements are achieved by converting existing irrigated areas from low efficiency systems (such as flood/gravity systems) to more efficient systems (such as drip and sprinkler systems). Efficiency improvements can be achieved through improvements made to existing flood/gravity irrigation systems through land leveling, better irrigation scheduling, or improved water distribution (Miao et al., 2018). As we described in Section 1.1, the investment support scenarios are implemented as different levels of subsidy on the large-scale capital costs and on-farm capital costs. Farmers are responsible for the operations and maintenance of the irrigation systems, which have been included in the model as production costs.

The unit costs of surface irrigation expansion are based on new irrigation construction costs taken directly from the unit costs estimates from Inocencio et al. (2005) which are based on a review of 314 irrigation projects spanning 50 countries in Sub-Saharan Africa, Asia, and Latin America and funded (or assisted) by the World Bank, Sub-Saharan African Development Bank and the International Fund for Agriculture Development that were implemented from 1967 to 2003. This source distinguishes between costs of new construction and costs of irrigation rehabilitation, which are both used in the investment module depending on the situation. We also estimate the cost of upgrading existing irrigation systems from less efficient to more efficient systems based on rehabilitation unit costs. The cost of depreciation and capital replacement is the final component of the irrigation investment cost and must be borne in order to keep the existing and newly built irrigation infrastructure in good working order in the long run.

The results presented in the following section of this working paper have been aggregated and presented at World Bank regions (see Abbreviations and Acronyms). Figures in this section primarily focus on the irrigation investments in constant year 2000 US dollars from 2010 to 2050 divided into irrigated area expansion costs, system upgrade costs, system efficiency costs, and depreciation costs. Supplementary figures of investment needs are available in the supplementary information. Section 1.3 of the supplementary information provides a detailed description of the irrigation cost module.

For the *Invest* scenario, investment costs for all developing countries for the entire period from 2010 to 2050 total $1.1 trillion, with annual costs at about $26 billion per year (Figure 1). The total costs are split almost half and half between irrigation expansion and depreciation, with only a small portion of the cost coming from irrigation upgrades and efficiency improvement. Upgrade and efficiency improvement costs are most relevant in the East Asia and the Pacific region, totaling almost $7 billion. Of note is the fact that the type of investment required changes over time; whereas most of the expansion investments occur toward the beginning of the time period, depreciation becomes the major expense toward the end of the time period. It is worth noting, that as irrigated area increases, depreciation costs also increase over time. In terms of regional composition of the investment, the largest share of the required investment (over 40% or $444 billion) takes place in East Asia and the Pacific, followed by South Asia ($211 billion) and Sub-Saharan Africa ($173 billion).

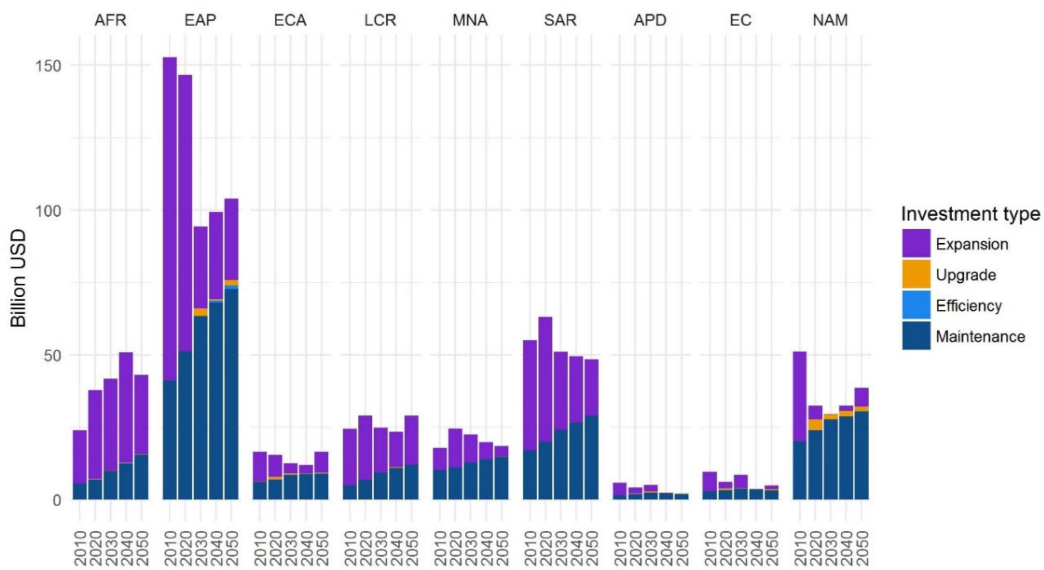

Figure 1. Total irrigation costs by type (expansion, upgrade, efficiency improvement, and depreciation) for the *Invest* scenario from 2010 to 2050 ($ billion, 2000 US dollar)

In *MaxInvest*, the investment costs for all developing countries total $2.0 trillion from 2010 to 2050 or $50 billion per year, meaning that the massive promotion of irrigation in this scenario would cost an additional $925 billion, or 85%, more than in *Invest* (Figure 2). Given the higher levels of irrigation expansion, the composition of investment costs is now tilted more in favor of expansion costs, which now total $1.3 trillion and comprise 65% of the total. Depreciation accounts for $659 billion and upgrades and efficiency improvements now also play a more important role at $33 billion. Investment under the *MaxInvest* scenario is slightly more evenly spread across regions, with East Asia and the Pacific accounting for 32% of the developing country total with $639 billion. Sub-Saharan Africa total investment of $429 billion ranks second before Latin America which ranks third with $343 billion.

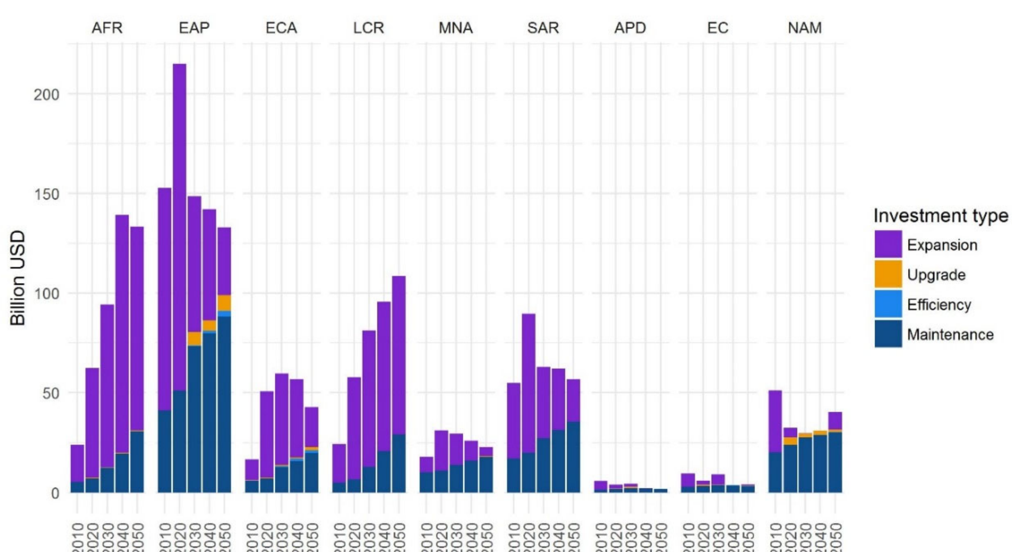

Figure 2. Total irrigation costs by type (expansion, upgrade, efficiency improvement, and depreciation) for the *MaxInvest* scenario from 2010 to 2050 ($ billion, 2000 US dollar)

Although *ZeroInvest* is a scenario in which no public investment in irrigation expansion occurs beyond 2010 levels, the existing infrastructure in developing regions is subjected to depreciation costs of $381 billion. Even with no investment in irrigation expansion beyond 2010, depreciation costs of already existing infrastructure must be borne regardless, and they continue to accrue through 2050. East Asia and the Pacific again ranks highest among regions with $187 billion of depreciation costs.

In the following two figures, we provide a comparison of investment requirements under the *Invest*, *MaxInvest*, and *ZeroInvest* scenarios with previous estimates from the literature, both for developing countries in total (Figure 3) and for Sub-Saharan Africa in particular (Figure 4). Directly comparing irrigation investment estimates is difficult given the differences in time horizons of the studies, methodologies, assumptions, and types of costs considered, some conclusions can nevertheless be drawn. Investment costs for *MaxInvest* are significantly larger than other studies considered as we model the largest expansion of irrigated area. Investment estimates for *Invest* are in the range of previous estimates, especially Briscoe (1999), FAO (2008) and Cosgrove and Rijsberman (2000). The investment needs from Winpenny (2003) builds on the estimates from Briscoe (1999) with a 15% allowance for maintenance and operation. These investment estimates lie slightly above that of the Invest scenario although they include investments for multipurpose uses as "agricultural projects" and therefore list hydropower investment needs as an agricultural investment. These costs are likely overestimated by as much as $10 billion to $12 billion. Molden (2007) project less area expansion and do not account for depreciation, a major expense. Schmidhuber et al.(2009) give support to the relative importance of depreciation costs in their estimates. Rosegrant et al. (2017) build upon the earlier work by Nelson et al. (2009) who estimated that additional investments in irrigation efficiency and a 25% expansion of irrigated area in developing countries would be needed to combat food insecurity resulting from climate change and could cost $3 billion per year. If we consider only the irrigation cost estimates for expansion, upgrade, and efficiency costs from the modest *Invest* scenario, and compare directly to the expansion and efficiency improvement costs in Rosegrant et al.(2017), the estimates from our study fall closely in line.

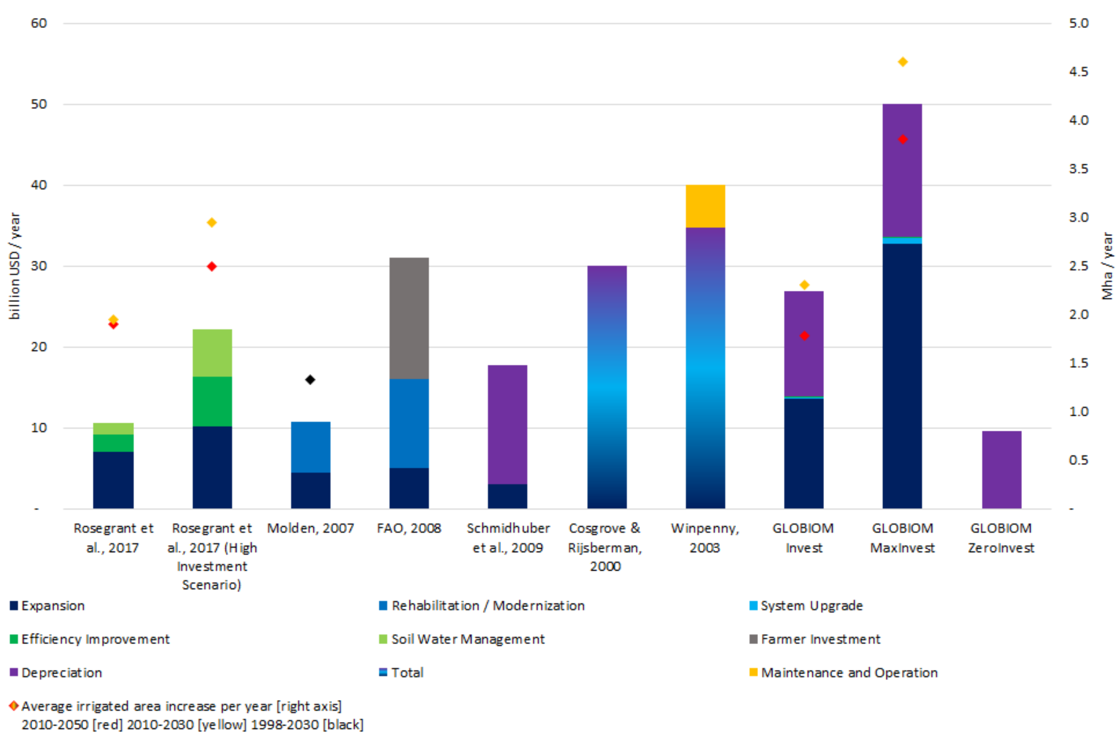

Figure 3. Average global annual irrigation costs by type and overview of estimates from literature for developing countries ($ billion, 2000 US dollar/year: primary axis, Mha /year: secondary axis)

In the case of Sub-Saharan Africa, our estimates are close to You (2008) and You et al.(2011) in terms of area expansion, but closer to NEPAD (2003) and FAO (2008) in terms of overall costs. This is explained by the difference in assumed per hectare unit costs of irrigation expansion in Sub-Saharan Africa, which are much lower in You (2008) and You et al.(2011) than in our approach.

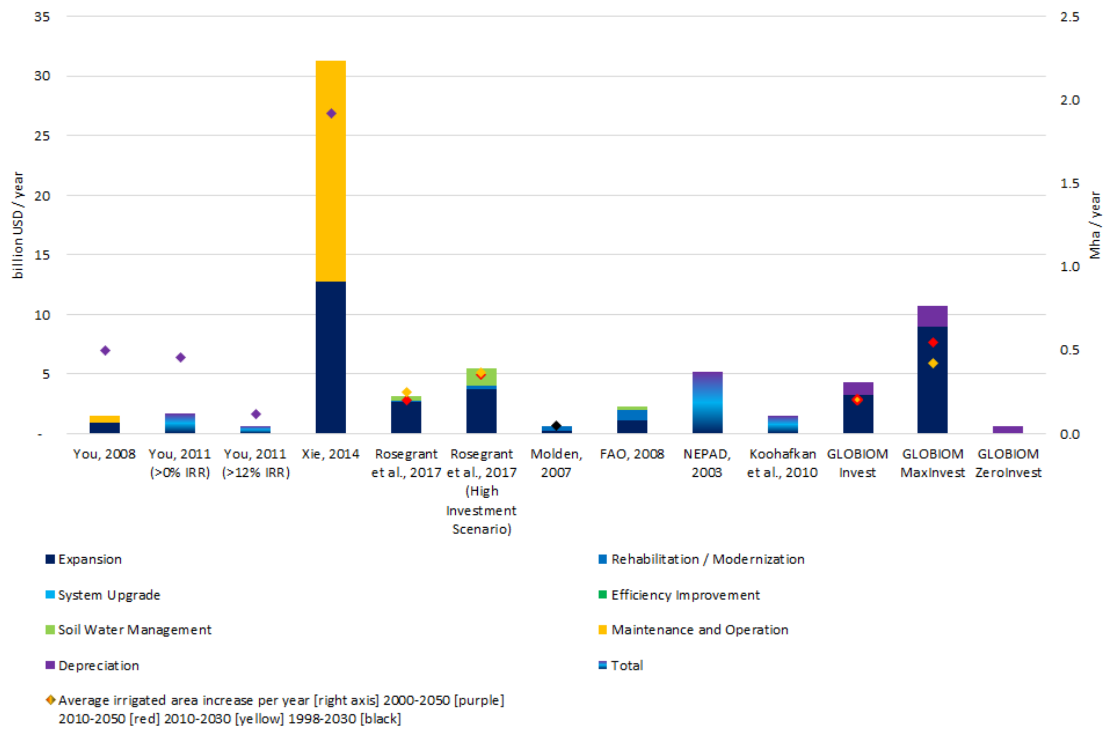

Figure 4. Average annual irrigation costs by type and overview of estimates from literature for Sub-Saharan Africa ($ billion, 2000 US dollar/year: primary axis, Mha /year: secondary axis)

3.2. Irrigation systems development

In 2010, about 91% of all irrigated areas in developing regions were under surface/gravity irrigation, 6% were under sprinkler, and 3% under drip irrigation (Figure 5). In the *ZeroInvest* scenario, irrigated areas decline in all developing regions. In *Invest*, surface/gravity irrigation systems continue to expand in all regions except ECA from 2010-2050, and sprinkler and drip systems expand in all regions (Figure 6). Of the expansion of surface/gravity irrigation systems (+48 Mha in *Invest*), 54% occur in SAR, 18% in EAP, and 13% in AFR, while in *MaxInvest* expansion of surface systems reaches 78 Mha. Of the new sprinkler systems (+8.1 Mha in *Invest*), 34% are constructed in EAP, 33% in LCR and 12% in AFR. In *MaxInvest* sprinkler system areas in 2050 are nearly four times higher than in 2010. 32% of the new drip irrigation areas (+15.8 Mha in *Invest*) are constructed in SAR and 41% of new areas are constructed in EAP (Figure 7). In *MaxInvest* drip irrigated areas are more than twice and a half times as high the drip area in *Invest*. By 2050, in *Invest* 85% of the total irrigated area in developing regions will be under surface/gravity, 7% under sprinkler, and 7% under drip irrigation, while in *MaxInvest* about three-quarters of irrigated areas use surface/gravity systems with the other two systems making up about 12% each. This shift in the share of irrigation systems to more efficient systems is due to an upgrading of surface systems to other irrigated systems and an expansion of irrigated areas.

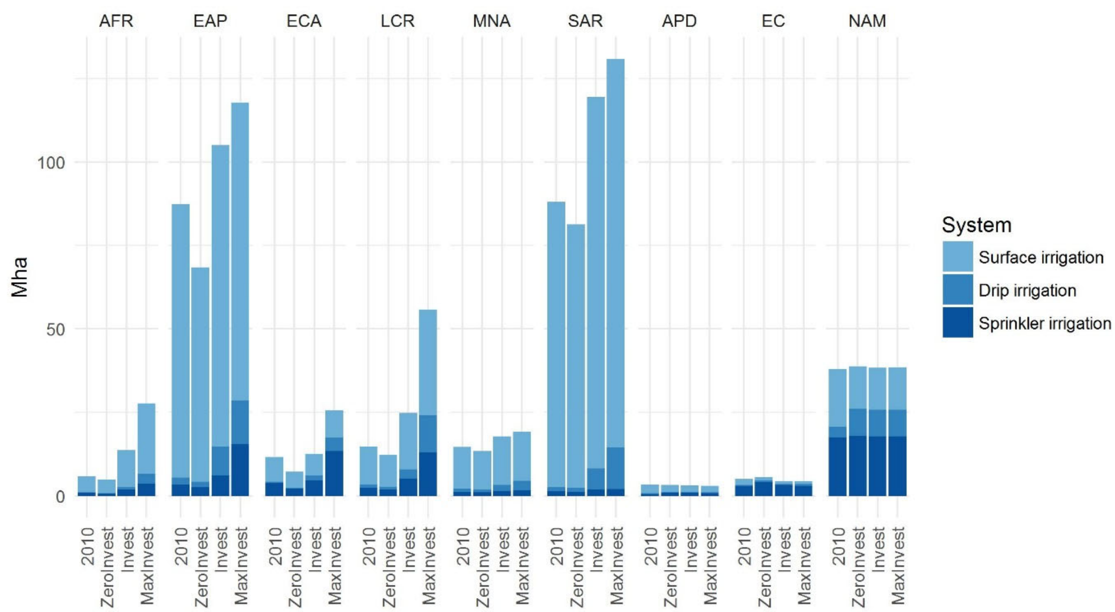

Figure 5. Irrigated area by system and region in 2010 and 2050 under *ZeroInvest*, *Invest*, and *MaxInvest* (Mha)

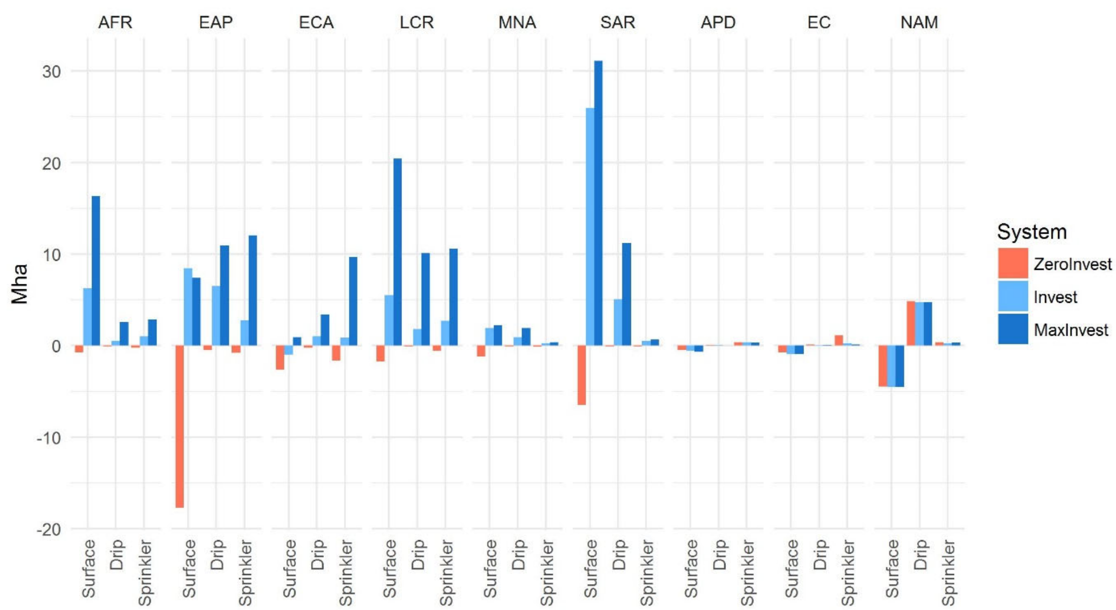

Figure 6. Net expansion of areas by system from 2010 to 2050 (net expansion excludes existing areas that are upgraded to more efficient systems or land retired/reverted to rainfed) (Mha)

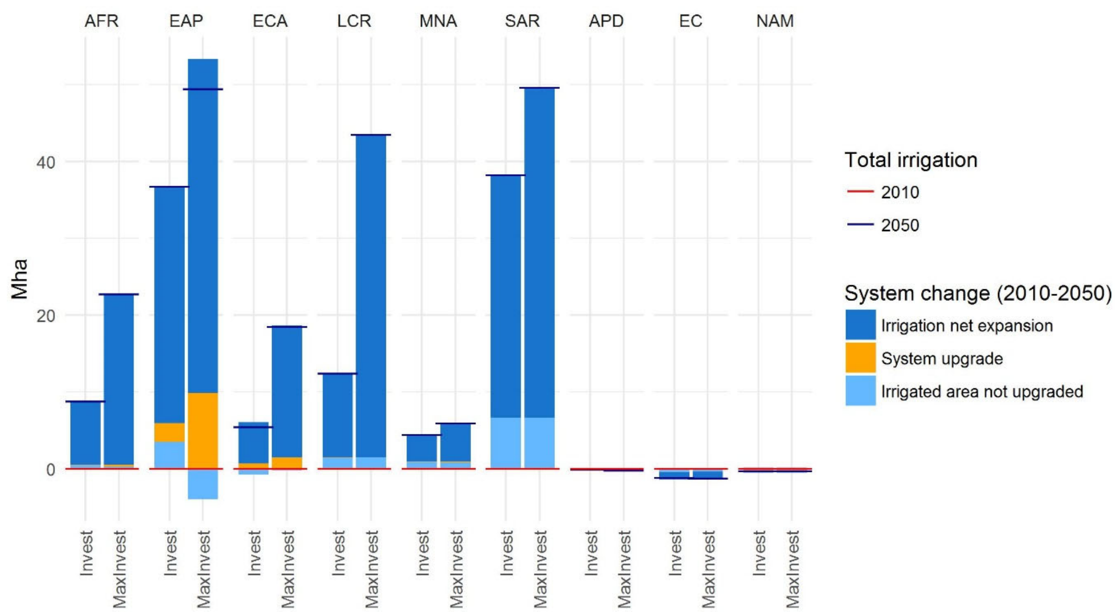

Figure 7. Cumulative irrigated area expansion and upgrade in *MaxInvest* and *Invest* from 2010 to 2050 (Mha)

4. Impacts of irrigation investments on SDGs

The investment scenarios above lead to large development of newly irrigated areas and impact a range of indicators in the agricultural sector and the sustainable development goals. We focus in our analysis on five different domains, modeled in GLOBIOM as below:

- economic development: crop production and net trade
- food security (SDG2): average daily per capita calorie availability
- climate change mitigation (SDG13): AFOLU (Agriculture, Forestry, and Other Land Uses) greenhouse gas (GHG) emissions
- terrestrial biodiversity (SDG15): cropland area, and area of forests and other natural vegetation
- sustainable water use (SDG6): irrigation water withdrawals and water efficiency

The results presented in the following sections have been aggregated and presented at World Bank regions level (see Section: Abbreviations and Acronyms). The figures in this section primarily focus on the impacts of irrigation investments from 2010 to 2050 but additional results and figures are available in the supplementary information: Section 2 for supplementary results, Section 3 for detailed regional results and Section 5 for supplemental figures of the impacts in 2030. Figures that can be found in the supplementary information are noted with "SI".

4.1. Rainfed and irrigated cropland

Portmann et al.(2010) estimate in 2000 about 24% of all cropland was irrigated, but for the crops modeled by GLOBIOM, about 30% of the total harvested cropland area was irrigated in 2000 (about 260 Mha globally). In 2010, irrigated cropland accounted for 30% of cropland or about 280 Mha (Figure SI 4 and Figure SI 5). Of the total irrigated area in 2010, 33% is located in SAR, 32% is located in EAP, 14% is located in NAM, 6% in LCR and 15% in all other regions (Figure 8).

The FAO estimates the global irrigation potential of approximately 515 Mha of which 292 Mha would be areas not currently under irrigation in 2010. Of this potential irrigation, 14 Mha are located in MNA, 58 Mha in ECA, about 30 Mha in both AFR and EAP, 76 Mha in LCR, and 82 Mha in SAR (FAO, 2017; Frenken, 2013, 2011, 2009, 2005) (Figure 9). These figures come from country case studies and in some cases consider only whether the land is biophysically suitable for irrigation, while others consider the natural resources and economic feasibility required to convert land to irrigation. We use the irrigated area potential as a benchmark for comparing the endogenous expansion of irrigated areas and not as a target or assumption in the modeling framework.

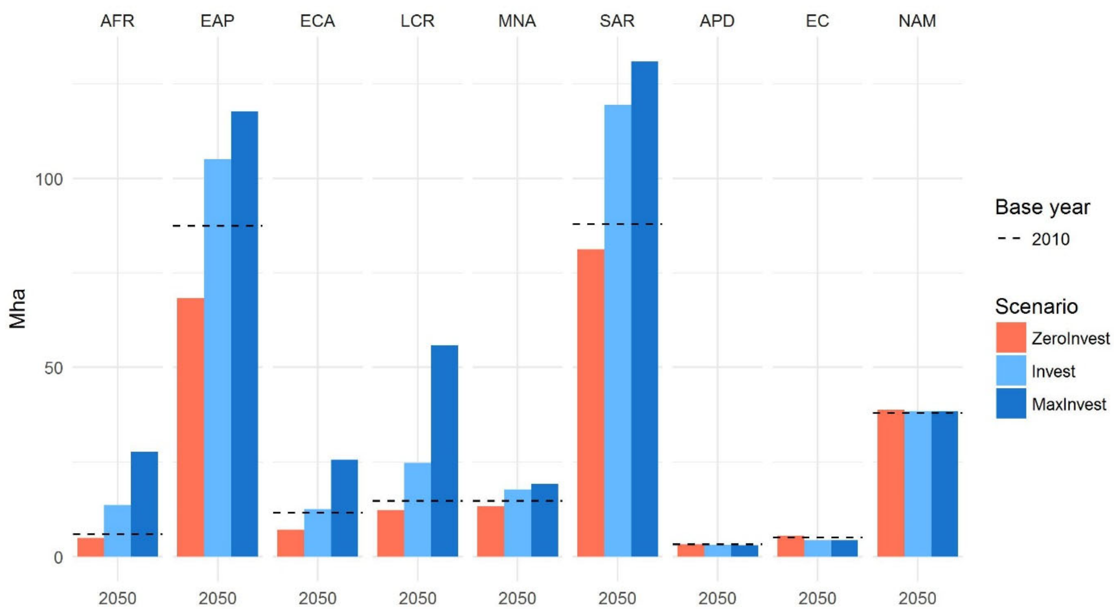

Figure 8. Irrigated area by region in 2010 and under *ZeroInvest*, *Invest*, and *MaxInvest* in 2050 (Mha)

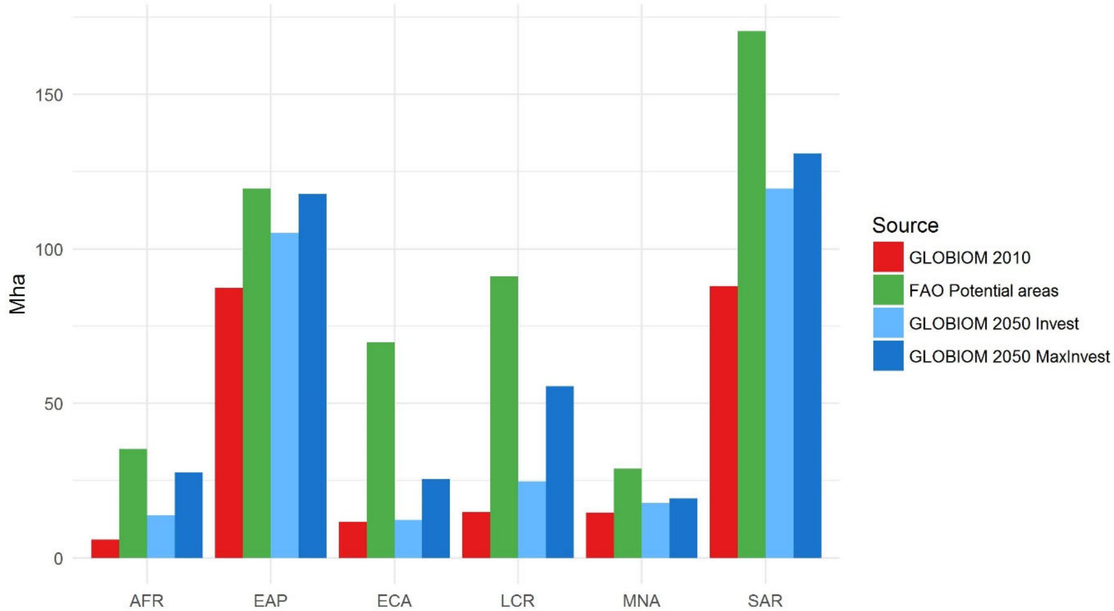

Figure 9. Irrigated area expansion in Max 2050 compared to FAO estimated irrigated area potential (FAO 2017) (Mha).

By 2050 under *ZeroInvest* and *Invest*, global cropland area expands by 181 Mha, while under *MaxInvest* cropland expands less (176 Mha) (Figure SI 3 and Figure SI 5). In *Invest* from 2010 to 2050, irrigated areas in developing regions expand 32% (71 Mha) and in *MaxInvest* irrigated areas in developing regions expand 70% (154 Mha), which means that the share of cropland area that is irrigated increases to about 41% (Figure 8). While in *ZeroInvest* due to a lack of investment, irrigated areas in developing countries decline by 2050 and the share decreases to 20% (Figure 8 and Figure SI 5). Compared to *ZeroInvest*, less area is needed for under cereal production in developing regions by 13 Mha in *MaxInvest* and 7.7 Mha in *Invest* although production is higher by about 2.4% *MaxInvest* (1.4% in *Invest*), implying that the investment support results in higher land use efficiency of the cereal production (Figure 10).

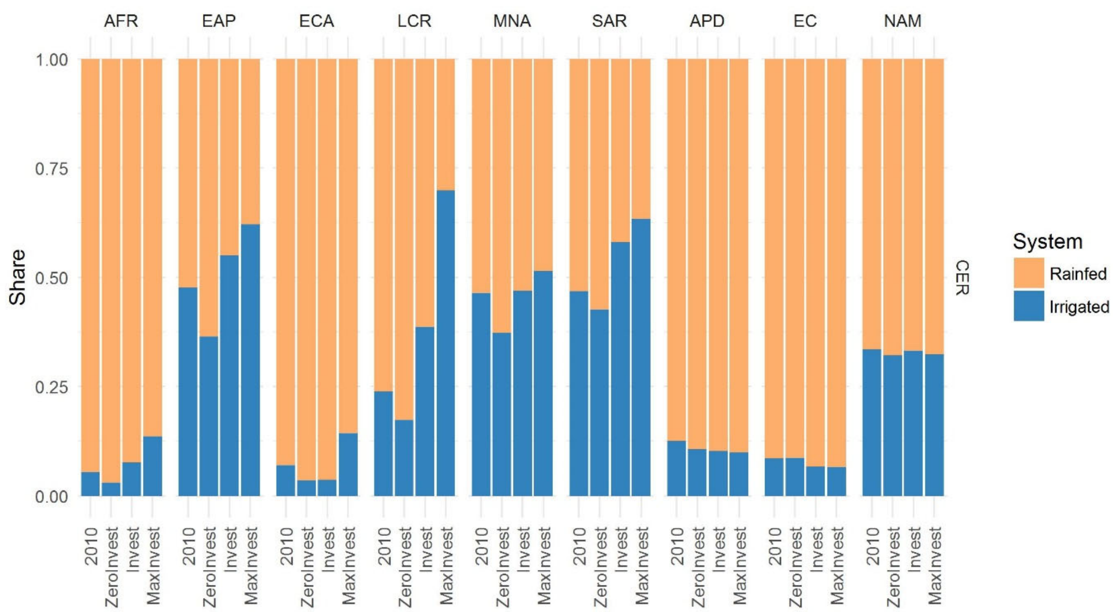

Figure 10. Share of cereal area that is irrigated in 2010 and 2050 in *ZeroInvest*, *Invest*, and *MaxInvest* by region (1.00 = 100%)

In 2010, 29% of the FAO potential irrigated areas are under irrigated area and with the expansion of irrigated areas in the *Invest* scenario this share of potential areas increases to about 55%, while *MaxInvest* the share of irrigated/potentially irrigated area increases to 72% by 2050. In some regions, the share is considerably higher: in EAP 84% of the potential area is converted, 62% in MNA and 68% in SAR. In ECA, the share of potential irrigated areas to areas converted to irrigation remains the largest in both *Invest* (only 18% of the potential area converted) and *MaxInvest* (only 34% of area converted) (Figure 9).

In a comparison of irrigated area expansion projections, de Fraiture and Wichelns (2010) find that the annual growth rates fall between 0.36% and 0.95% per year in scenarios from 2000-2030, and from 2010-2030 irrigated area grows 0.72% per year in *Invest* and 1.02% per year in *MaxInvest* and continues to grow by 0.25% per year from 2030-2050 in *Invest* and 0.31% in *MaxInvest*.

4.2. Production

In 2010, about 75% of the total crop production is produced in the targeted developing regions (MNA, AFR, ECA, SAR, LCR), and in 2050 that share increases to 80% in the *Invest* scenario. Under *Invest*, global crop production increases 73% from 2010 to 2050 (5.3 trillion tonnes dm) and nearly doubles by 2100 (Figure SI 8). Under *MaxInvest* global production in developing countries increases by an additional 4% in 2050 but without additional expansion of irrigated area (*ZeroInvest*), global crop production will expand less (-5%) than *Invest* in 2050 (Figure 11).

Global production is driven by changes in crop demand and changes in crop prices but examining the relative differences in regional production allows us to identify regions where the scenario investments in irrigation infrastructure increase the region's production contributions. *MaxInvest* delivers the most benefits to EAP and LCR, where, compared to *Invest*, total crop production is larger by 2% and 3% in 2050 and other regions like NAM and EC decrease production (-8% and -4%) (Figure 11).

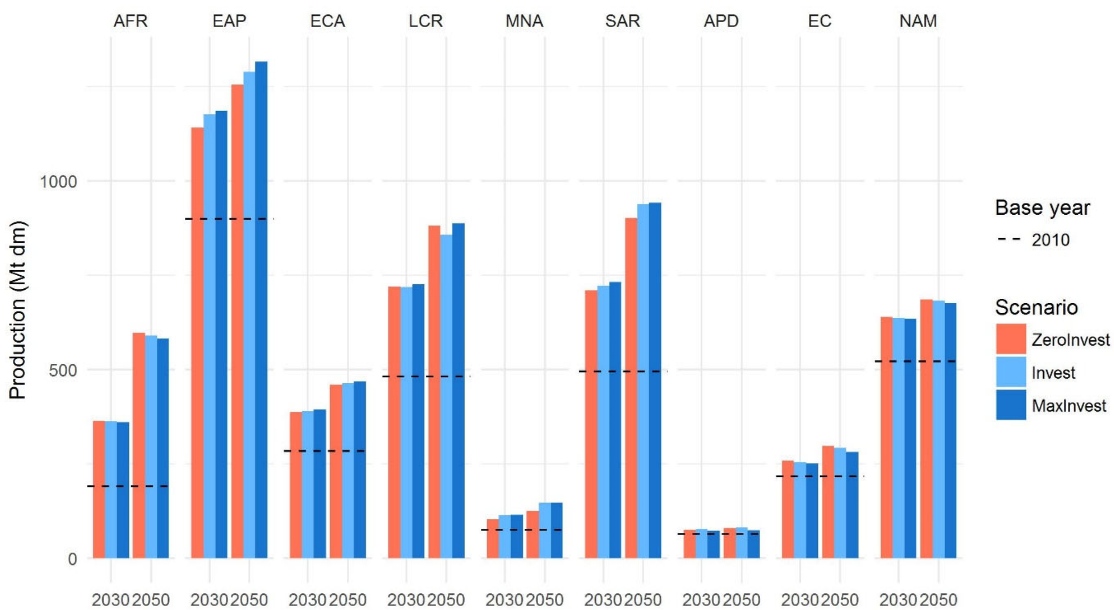

Figure 11. Total crop production in 2030 and 2050 in *ZeroInvest*, *Invest* and *MaxInvest* (Mt dm)

The relative gains in LCR and EAP for *MaxInvest* benefit the producers in the region, but also reduce the potential gains for the other developing regions. In a strategy for irrigation investment that targets only individual regions rather than all regions (called Region *MaxInvest*), the benefits, in terms of total crop production, in the target region are always larger than that of the *Invest* scenario and the *MaxInvest* scenario (on average about 3 percent higher than *Invest* in 2050, and 2 percent higher than *MaxInvest* scenario). However, the global crop production for the Region *MaxInvest* scenario is always lower than under the *MaxInvest*, meaning that no target region produces more than the total production under the global strategy (Figure 12). Although relatively small compared to the overall trend and impact of the investment scenarios, the rebound effect of investments in competitive regions like EAP and LCR on less competitive regions should be considered.

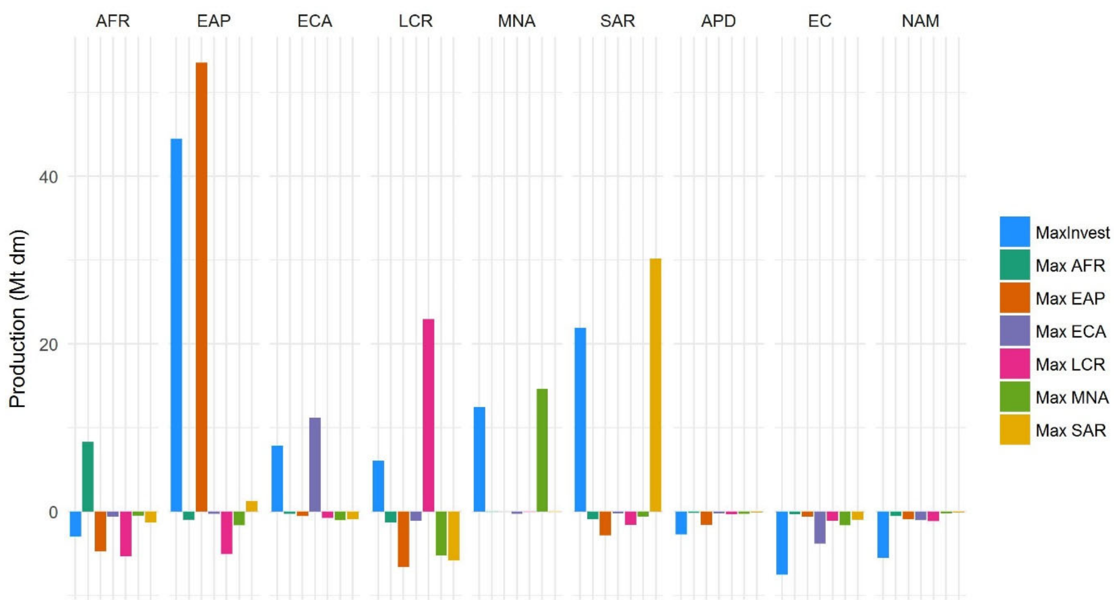

Figure 12. Difference in crop production under regional maximum investment scenarios compared to *ZeroInvest* in 2050 (Mt dm)

The share of global cereal supply that was produced using irrigation was about 40% in 2010 (Portmann et al., 2010). Cereals represented in GLOBIOM include rice, wheat, corn, barley, sorghum and millet. In 2010, developing regions supplied approx. 70% of the total cereal and 72% of the irrigated cereal, 75% of the total crop products and 76% of all the irrigated crop supply.

In the *Invest* scenario by 2050, the irrigated share of global cereal production increases to 45% and the share of irrigated production of cereal and all crops increases to 54% in *MaxInvest*, while in *ZeroInvest* the share decreases to 32% for cereals and 29% for all crops by 2050.

By 2050, developing countries in the *Invest* scenario contribute more than 79% of the irrigated cereal supply and in *MaxInvest* 83% of the irrigated cereal supply.

In the *MaxInvest* scenario the share of irrigated cereal supply in developing countries increases on average by 18%, and 6% in *Invest*, though the changes in shares are quite heterogeneous by region. In *Invest*, LCR increases the share of cereal production coming from irrigated areas from 30% to nearly 50%, EAP from 53% to 60%, and SAR by from 56% to 67% (Figure 19). In *MaxInvest*, AFR increases from 10% of total cereal production to 20%, SAR from 56% to 75%, LCR from 30% to 78%, and EAP from 53% to 67%. Section 2.2 in the supplementary information provides additional discussion on each region's production contribution to global cereal production.

4.3. Food self-sufficiency and net trade

Examining a region's imports or exports as a share of the domestic consumption allows us to assess the agricultural self-sufficiency or dependence on the outside world. We calculate not only the net trade but the net trade as a share of the region's domestic market to analyze the impact of irrigation investments on imports or exports. If the share value is positive it indicates that the agricultural product is exported and it if is negative it indicates that the product is imported. In MNA, under the investment scenarios the self-sufficiency for the region (Figure 13). More than 70% of the production in MNA is irrigated and further investments would allow for expansion of irrigated cropland. In AFR, the region's self-sufficiency improves for a few crops, rice, potatoes, soybean however, net trade as a share of the domestic market is still negative under the investment scenarios, although the trade share of cereals in *Invest* and AFR Regional *MaxInvest* is lower than *ZeroInvest* (Figure 15). Since most of the region's production is grown on rainfed area, the most ambitious investments do not lower all crop prices enough to compete with the products produced outside the region. In EAP in *ZeroInvest* in 2050, the region is a net importer of crop products, while the investment scenarios do not flip the trade balance, the *MaxInvest* and EAP Regional *MaxInvest* significantly reduce imports (Figure 14). In LCR, the region is a significant exporter of crop products. The investments in irrigation under *Invest* and *MaxInvest* reduce the share of exports in LCR, however in LCR Regional *MaxInvest*, the region exports most as it is able to take advantage of its comparative advantage, including increasing the share of cereal exports by almost 4% (Figure 14). In SAR, total net trade of crop products as a share of the domestic markets are slightly reduced under the irrigation investment scenarios, essentially increasing the self-sufficiency of the region. However the basket of crops changes such that the region becomes an increased net importer of cereal products.

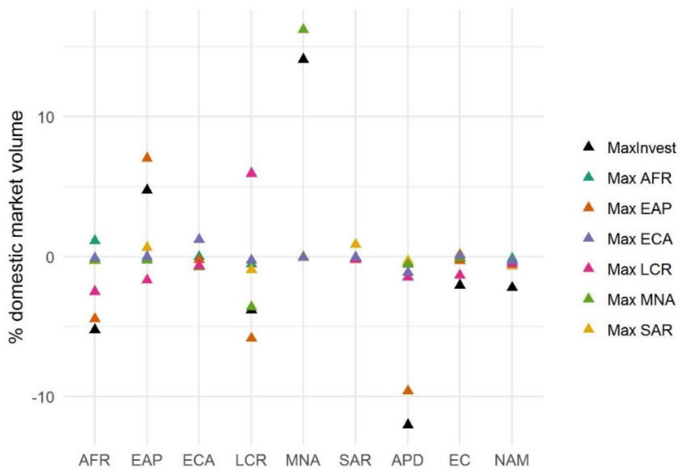

Figure 13. Difference in trade as a share of the domestic market volume compared to *ZeroInvest* in 2050 (%)

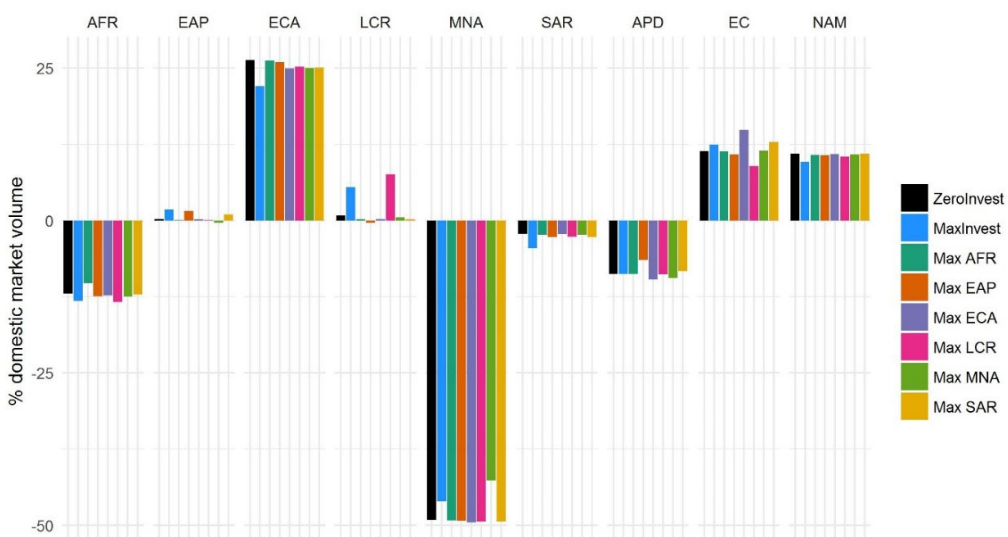

Figure 14. Net trade as a share of the domestic market for cereals in 2050 (%)

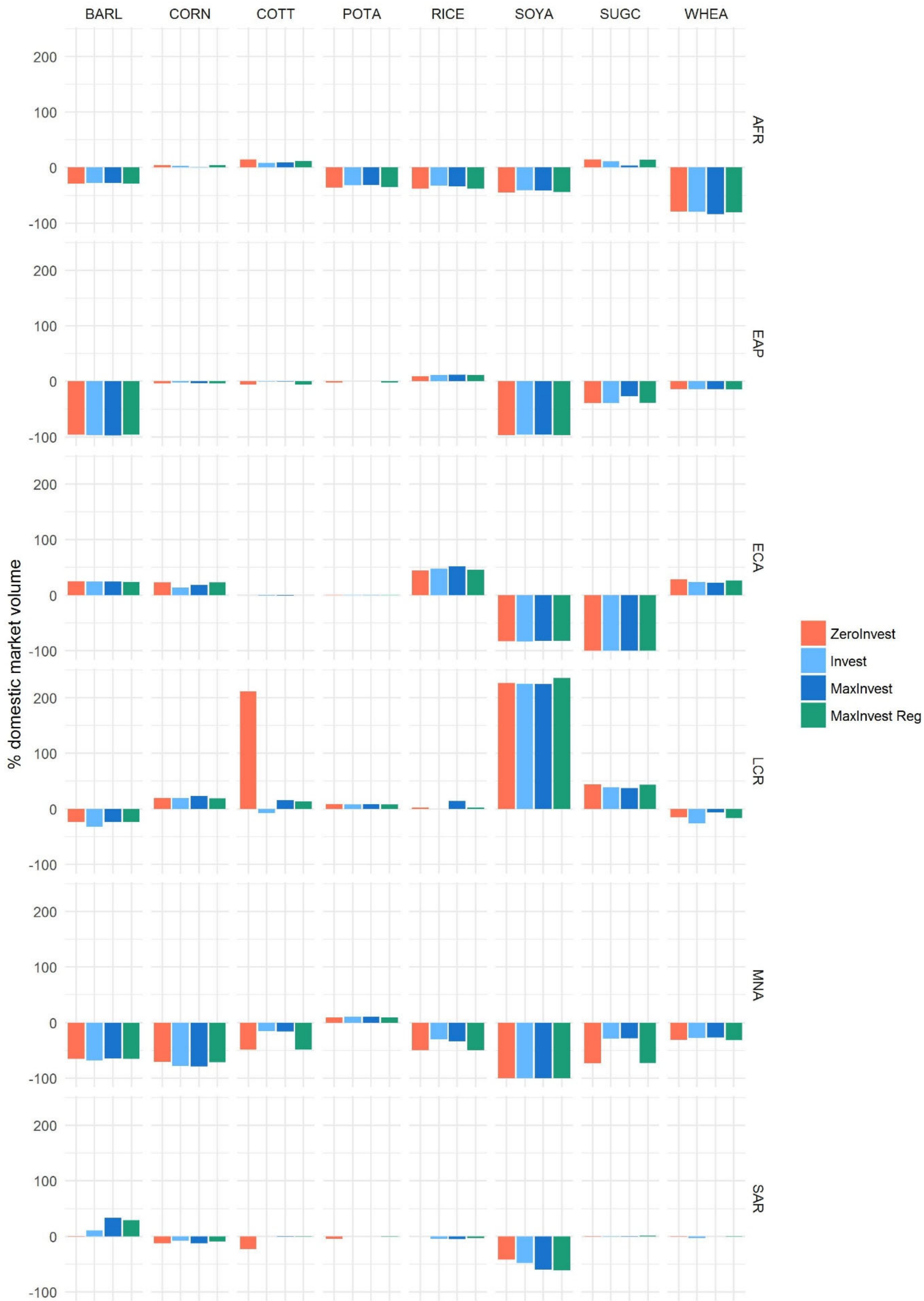

Figure 15. Net trade as a share of domestic consumption by crop in 2050 under *Invest*, *MaxInvest*, *ZeroInvest*, and the regional *MaxInvest* scenario (%)

4.4. Food security

We use the demand for crop and livestock products for food as an indicator of the food security needs of a wealthier, growing population (Valin et al., 2014). Our analysis uses kilocalorie availability per capita per day which is a measure of the total final demand of households or food available for consumption which does not include retail waste but does include household waste. In terms of food availability, FAO considers 2500-3000 kcal/capita/day to be a target for developing countries (Alexandratos and Bruinsma, 2012). Calorie availability per capita per day increases in all regions from 2010 to 2050 under both *MaxInvest* and *ZeroInvest*, where the global average increases by at about 14% (Figure 16). Calorie availability is higher in all regions in the *MaxInvest* scenario, with the largest difference in calories in LCR, EAP, and SAR. Calorie availability in almost every region is lower under the Region *MaxInvest* scenarios compared to the *MaxInvest* scenario. For the targeted region of the Region *MaxInvest* scenario, the calorie availability is of course higher than the calorie availability for the region under non-targeted Region *MaxInvest* scenarios. For example, calorie availability for the EAP Region *MaxInvest* is only 0.08% lower than *MaxInvest*, while for the other Region *MaxInvest* scenarios is about 1% lower than *MaxInvest*. The difference in the global average calorie availability under the Region *MaxInvest* scenarios is about 1-2% less than *MaxInvest*, however in LCR and SAR, the calorie availability is about 4% to 5% less than under *MaxInvest*. This implies that regional investment strategies succeed to improve the food security of the regions they target but achieving across the globe food security requires investments in all the regions.

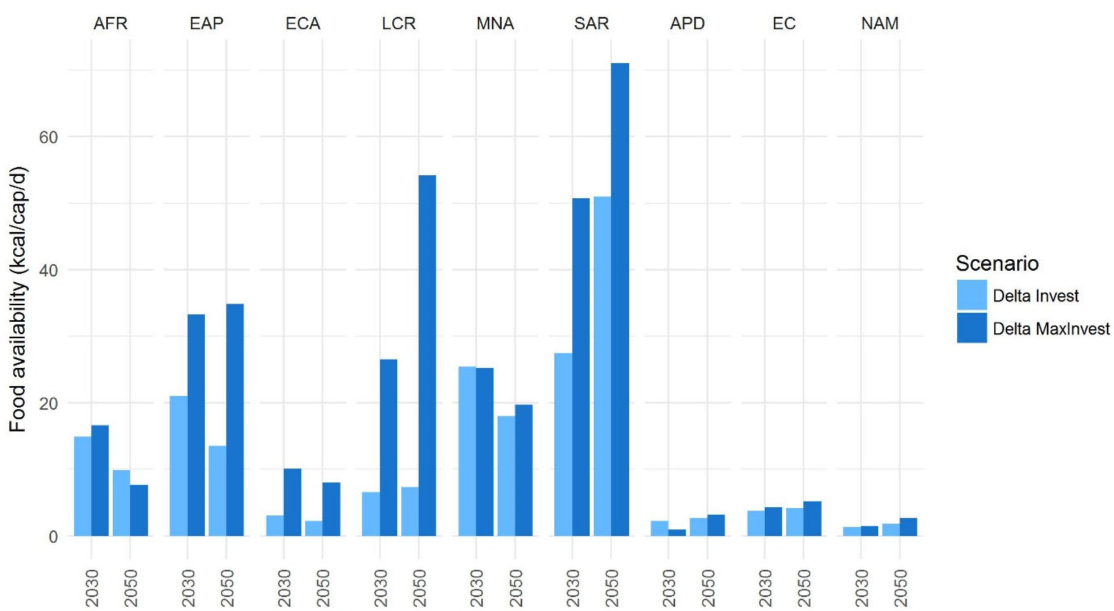

Figure 16. Difference in kilocalorie per capita per day by region compared to *ZeroInvest* in 2030 and 2050

4.5. Land use change

Irrigation can increase the productivity of cropland and in some cases reduce the total cropland required for production, however when cropland becomes more profitable under irrigation it can have the opposite effect and increase cropland expansion. By 2050 under *ZeroInvest* and *Invest*, cropland area expands by 181 Mha, while under *MaxInvest* cropland expands less (175 Mha). Section 2.3 in the supplementary information provides a more detailed discussion of the impacts of irrigation investments on land use change in each region.

4.5.1. Conversion of forests

In *ZeroInvest*, 145 Mha of forest area are converted from 2010 to 2050, about half from AFR, 34% from LCR, and 17% from EAP (Figure 17, Figure SI 17). In *MaxInvest*, an additional 6 million more hectares of forest area are converted, those these primarily occur in LCR and EAP. More forest area is converted in *MaxInvest* in AFR than under *ZeroInvest* (72.3 Mha and 71.8 Mha respectively), and more forest area is converted in the most of the Regional *MaxInvest* scenarios than in the *ZeroInvest* scenarios. Nearly 500,000 more ha of forest area is converted in AFR in the EAP Regional *MaxInvest* scenario than under *MaxInvest*. In LCR, *MaxInvest* and the LCR Regional *MaxInvest* see the most forest area converted, 54.9 Mha in both, while the target region scenarios have conversion of less area than the *ZeroInvest*. Conversion of forest area in EAP in the EAP *MaxInvest* scenario is 5.2 Mha higher than in *ZeroInvest* (24.2 Mha).

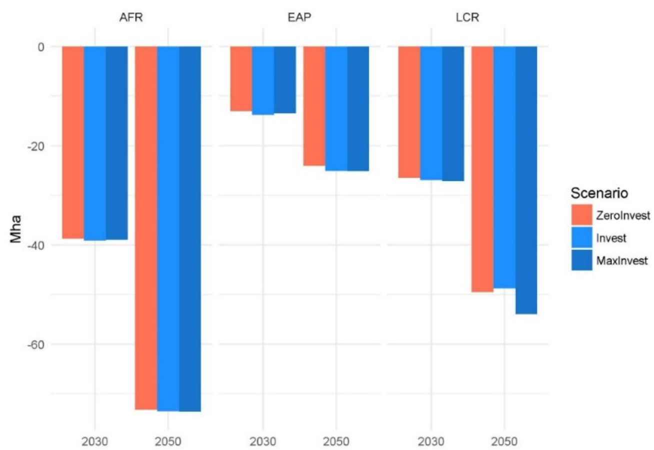

Figure 17. Total forest area change between from 2010 to 2030 and 2050 (Mha)[4]

4.5.2. Conversion of other natural vegetation

More than 297 Mha of other natural land are converted to grassland and cropland globally in *ZeroInvest* and *Invest*, but in *MaxInvest* only 286 Mha are converted (Figure 31, Figure SI 17). While deforestation in *MaxInvest* is approximately 4% higher in 2050 than *ZeroInvest*, total land use change in *MaxInvest* (forest and natural land conversion) is 1% lower. In *ZeroInvest*, most conversion of other natural land occurs in AFR and EAP, 87.1 Mha and 66.6 Mha respectively (Figure 18).

[4] Other developing regions are removed from this figure as they have no deforestation (ECA and MNA) or only minor deforestation 200,000 ha (SAR) in the results.

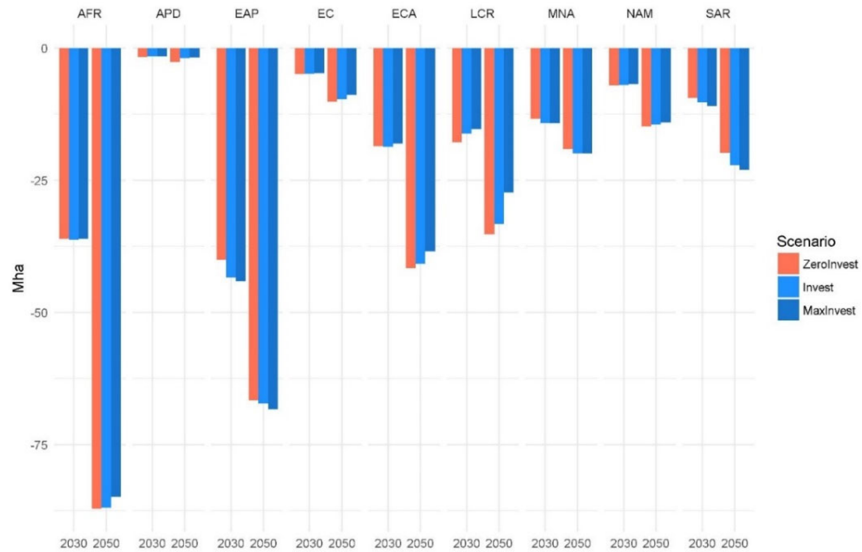

Figure 18. Total other natural land area converted to agricultural land in 2030 and 2050 (Mha)[5]

[5] Figure 18 also includes cropland areas that have been abandoned and are reverted back to other natural land.

4.6.GHG emissions

Examining emissions from the AFOLU (Agriculture, Forestry, and Other Land Use) sector allows us to contextualize climate stabilization through the impacts of expanded afforestation and biomass production for energy use, land use change such as deforestation and conversion of natural land to grassland and cropland, and the impacts of production of crop and livestock products. GHG emissions from land use change and agricultural production increase by 45% from 2010 to 2050 in *Invest*, 46% in *MaxInvest* and 43% in *ZeroInvest* with the most GHG emissions occurring in East Asia (Figure 19, Figure SI 31). The largest percent increase in GHG emissions from 2010-2050 comes from AFR, where emissions increase 76% in *Invest* and 77% in *ZeroInvest*.

Globally, emissions are slightly higher in *Invest* and *MaxInvest* compared to *ZeroInvest* (138 and 224 Mt CO_2 eq higher in 2050, respectively) due to increased carbon emissions from soil (72 and 88 Mt CO_2 eq higher than *ZeroInvest* in 2050), livestock production (61 and 58 Mt CO_2 eq higher in 2050) and land use change from deforestation and conversion of natural land for crop and grassland (9 and 88 Mt CO_2 eq higher in 2050 than *ZeroInvest*).

Livestock production accounts for the largest share of agricultural GHG emissions in 2050 (about 61% of the total GHG emissions in 2050 in all scenarios), with half coming from EAP and LCR. Land use change is responsible for the second largest share of total GHG emissions in 2050 (19%). Slightly more than half of the LUC emissions occur in Sub-Saharan Africa in all scenarios, though LUC emissions in *ZeroInvest* are higher than in *Invest* and *MaxInvest*. 38-42% of LUC GHG emissions come from EAP and LCR, where in LCR the emissions from LUC under *MaxInvest* are about 30% higher than under *ZeroInvest*. Section 2.4 in the supplementary information provides additional discussion on each region's GHG emissions under the investment scenarios.

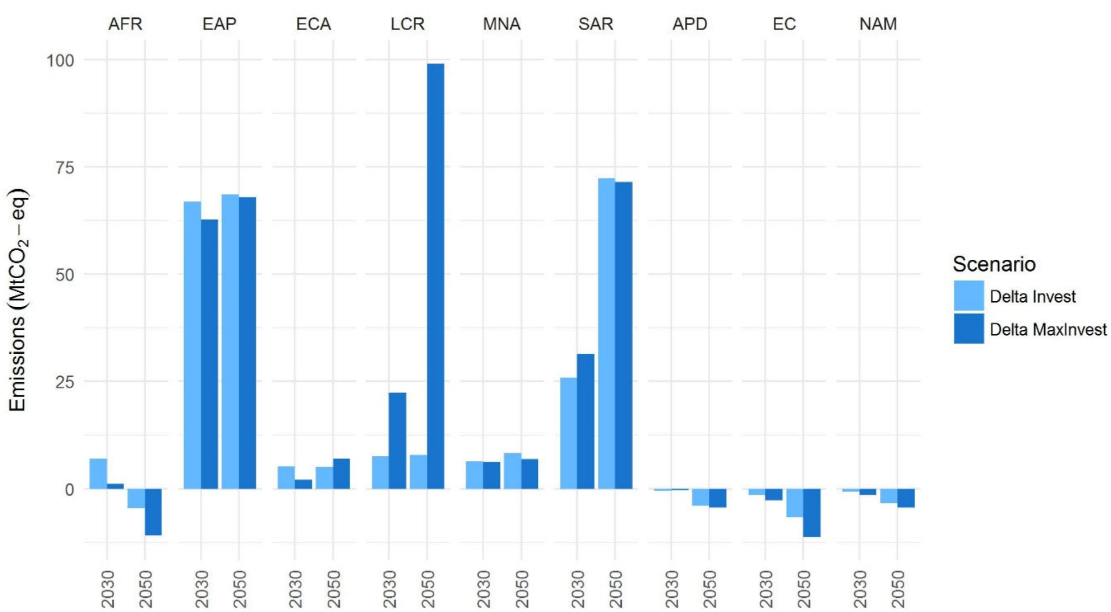

Figure 19. GHG emissions from crop and livestock production and land use change in 2030 and 2050 compared to *ZeroInvest* (Mt CO_2eq/yr)

4.7. Water Withdrawal

4.7.1. Water withdrawals from other sectors

In our modeling approach, agriculture is the residual user of water, meaning that the demand for water for domestic and industry/energy takes priority over agriculture, which is a standard followed within the community (Bonsch et al., 2016; Robinson et al., 2015). Sectoral demands are important to consider as the change in demand for other uses can in some cases exceed the current and future water availability (Figure 39). Projections from the Water Futures and Solutions fast-track modeling effort were used to model water demand from domestic and industrial/energy users (Wada et al., 2016). For this analysis we use the water demand projections from PCR-GLOBWB (van Beek et al., 2011; Wada et al., 2011, 2010; Wada and Bierkens, 2014) which calculates the water demand dynamically with water availability using the feedbacks on from demand on the water availability and vice versa. Future development of irrigation infrastructure should consider the potential competing demand for water from other sectors as well as how these demands may impact the water availability throughout the year (Wada et al., 2014).

Water withdrawals for domestic and industrial users are expected to increase 40% by 2020 and nearly double by 2050 (Figure SI 32). In 2010, ECA, which includes the Russian Federation, withdraws the most water for any non-agricultural water use, 300 km^3, followed by NAM and EC for industrial water use, 230 km^3 and 112 km^3, respectively. Withdrawals for domestic use are highest in EAP (90km3) followed by ECA and NAM (66 km^3 and 62 km^3). By 2050 in SSP2, industrial water demands are expected to triple (more than 400% in EAP and 200% in ECA). Domestic water withdrawals are to increase nearly 400% by 2050 in SSP2, with much of the growth coming from the regions EAP, SAR, AFR, LCR, and ECA (Wada et al., 2016) (Figure 20).

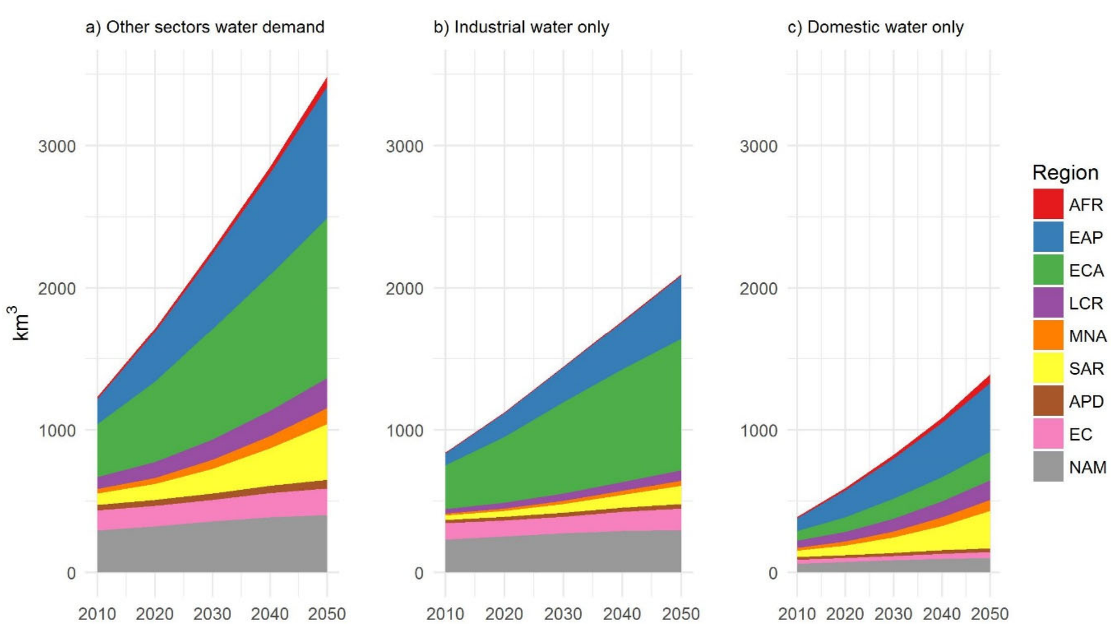

Figure 20. Water demand for total (industrial and domestic use) (a), industrial uses (b), domestic uses (c) from 2010 to 2050 under SSP2 from PCR-GLOBWB prepared for WFaS fast-track (km3) (Wada et al.2016).

4.7.2. Irrigation water withdrawals

Irrigation withdraws most surface water globally, 55% of the total surface water and 70% of all water withdrawals in 2010 (Figure SI 32). In 2000, irrigation withdrawals were about 2,500 km^3 and we estimate that they reached about 2,600 km^3 of water by 2010, which falls in between other global estimates of irrigation water withdrawals (Wada et al., 2014). We assume that groundwater extraction is restricted to 2010 levels, but that surface water can continue to be withdrawn for irrigation within the limits of monthly flows and after the demand from other users is satisfied.

In some regions, the withdrawals for irrigation account for more than 75% of the total extractions from surface water (EAP, SAR, AFR, MNA) (Figure 21). Developing countries contributed to 86% of the total water withdrawn for irrigation in 2010, more specifically EAP and SAR are responsible for nearly 60% of the total. MNA withdrawals were 10% of the total irrigation water demand, followed by NAM (8%), LCR (7%), and ECA (6%).

Although agriculture is the residual user of water, irrigation water withdrawals increase about 20% by 2050 in the *Invest* scenario and almost 70% in the *MaxInvest* scenario (compared to 2010), while withdrawals for irrigation in *ZeroInvest* in 2050 decline by more than 10%. In *MaxInvest* the share of the total irrigation withdrawals coming from developing countries increases to more 90% in 2050.

In *MaxInvest*, the withdrawals for irrigation in AFR and LCR increase most dramatically over the time period, almost 319% and 266% respectively, though withdrawals in EAP in 2010 were the largest (728 km^3) and continue to increase (+53% in 2050 in *MaxInvest*, +9% in *Invest*) (Figure 22). In SAR, withdrawals were about 826 km^3 in 2010 and will continue to increase by 26% in *Invest* and by 52% in *MaxInvest* in 2050 (Figure 22).

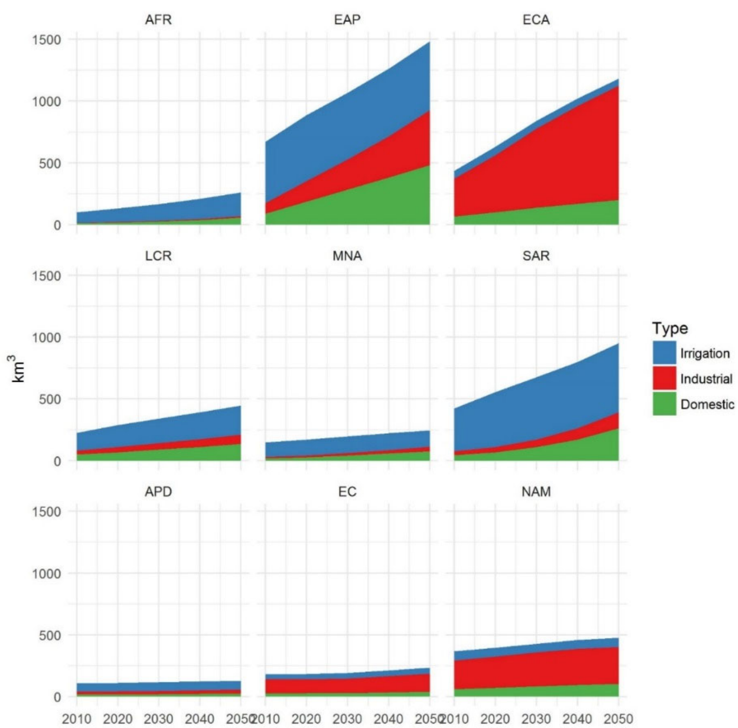

Figure 21. Surface water withdrawals[6] by sector and region from 2010 to 2050 in the *Invest* scenario (km^3)

[6] Irrigation water withdrawals in Figure 21 in do not include other sources such as groundwater to allow for comparing the surface water extraction across sectors.

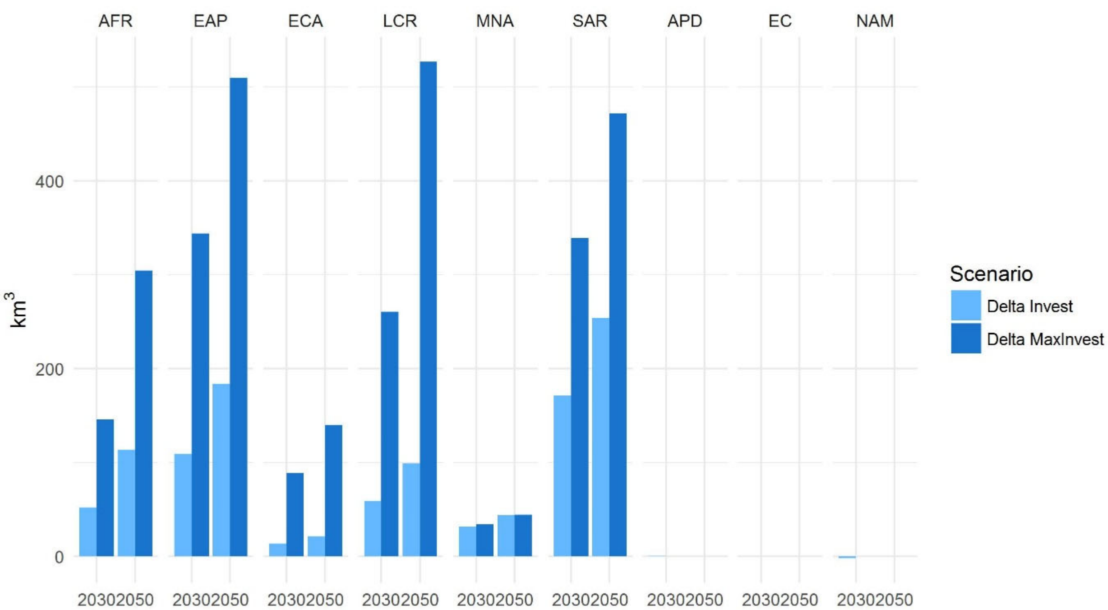

Figure 22. Total water withdrawal for irrigation from all sources compared to *ZeroInvest* in 2030 and 2050 (km^3)

4.7.3. Unsustainable irrigation water withdrawals

Agriculture is the residual user of water, however, without streamflow protection measures, the demand for water for irrigation and from other uses could exceed the quantity of water that should be left for the environment, called environmental flow requirement (EFR). EFRs are calculated based on the variable monthly flow (Pastor et al., 2014), which changes depending on the monthly stream discharge levels. Without explicitly restricting irrigation withdrawals under *MaxInvest* and *ZeroInvest*, we identified locations where the monthly irrigated surface water demand was unsustainable, meaning that agriculture would consume a portion of the streamflow that should be left for the environment. The monthly level is critical to evaluate environmental flow protections since more than half of the river basins have at least one month in a year of unsustainable water withdrawals (Hoekstra et al., 2012) and minimum flows that do not consider the variable flow patterns of river systems will fail to protect the riverine ecosystem (Arthington et al., 2006; Pastor et al., 2014).

In 2010 in the MNA region, the share of the total irrigation surface water demand that is unsustainable is greater than 15%, while in SAR the share is between 10 and 15% of the total surface water demand (Figure 23). In 2010, about 11% of the global surface water withdrawals for irrigation consume water that should be left for the environment, and 36% of the total global surface withdrawals for irrigation are at risk to consume water which should be left for the environment. Globally, the quantity of surface water withdrawals for irrigation increases by 34% in *Invest* and 124% in *MaxInvest* and the quantity of unsustainable water increases by 39% in *Invest* and 130% in *MaxInvest* by 2050 (Figure 22, Figure 23).

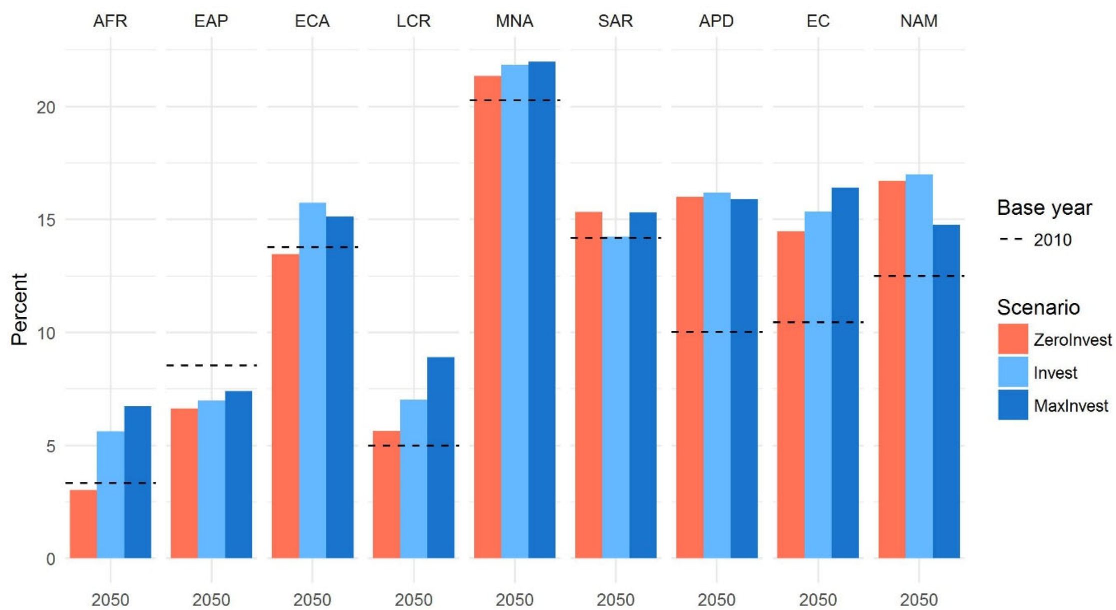

Figure 23. Surface water withdrawals for irrigation considered unsustainable as a share of the total surface water withdrawals for irrigation by region in 2050 (%)

Although the share of unsustainable irrigation surface water demand at an aggregate level can signal a larger problem of resource management within the region, unsustainable extraction from streamflows should be examined at a river basin level or lower. In regions with significant surface water extraction, the share of withdrawals that are unsustainable may appear relatively small but may be clustered in one location. For example, in 2010, surface water withdrawals for irrigation in East Asia and the Pacific, were 496 km^3 (55% of the total water withdrawals for the region). Of the region's total surface water withdrawals about 42 km^3 were considered unsustainable, which is about 9% of the region's total surface water demand (Figure 23, Figure 24). However, the region's total surface water withdrawals in areas with at least one month of unsustainable water withdrawal was about 158 km^3, which is about 32% of region's total surface water withdrawals for irrigation (Figure 24). The unsustainable surface water withdrawals for irrigation as a share of the total environmental flow requirement in locations with unsustainable water withdrawal is significant in some regions (Figure 23, Figure 24, Figure SI 34).

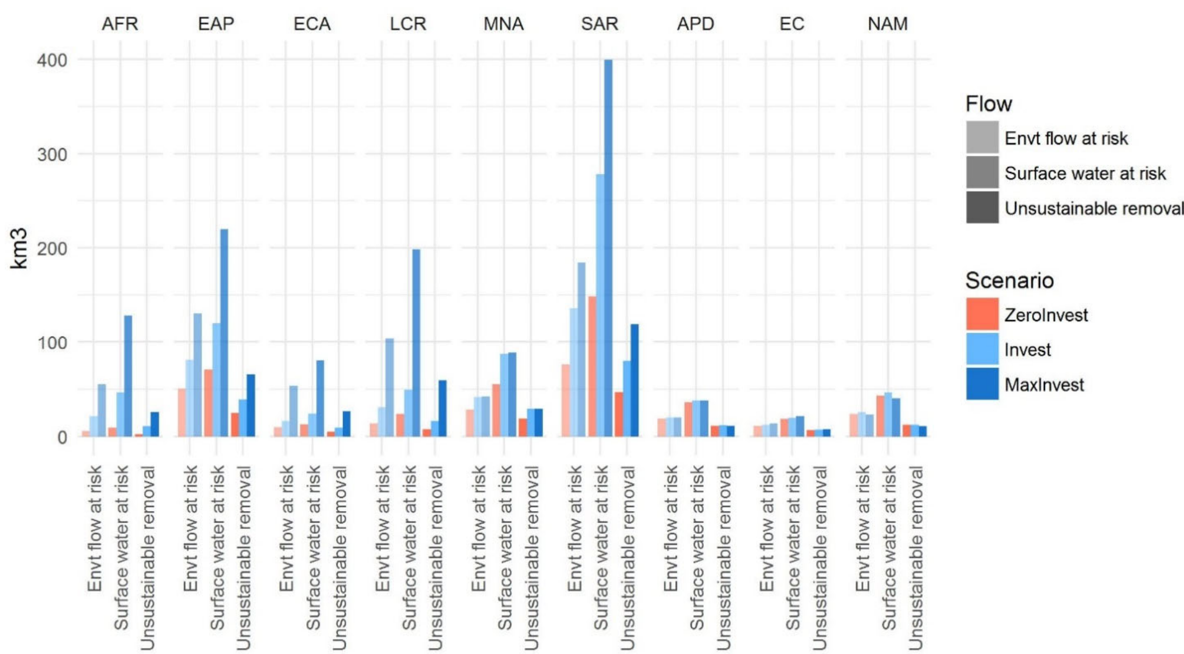

Figure 24. Comparison of surface water withdrawals considered unsustainable ("Unsustainable removal"), irrigation surface water withdrawals taking place in locations at risk for unsustainable withdrawal ("Surface water at risk"), environmental flow at risk by irrigation ("Envt flow at risk") in 2050 (km^3)

5. Contextual uncertainty analysis

To evaluate the uncertainty of the impacts of irrigation investment strategies within our modeling framework, we conducted a sensitivity analysis around various modeling assumptions and drivers.

The baseline assumptions of SSP2 are varied across different sensitivity analyses. We tested the sensitivity to some key parameters: i) socioeconomic change, ii) climate change impact magnitude, iii) change in dietary patterns, iv) trade openness, v) water use efficiency.

We further combined various parameters and assumptions of the uncertainty scenarios to form more extreme scenarios. The goal of these "extreme scenarios" is to identify the smallest and largest expansion of irrigated areas as well as the least and greatest irrigation investment costs that would be required for those areas. The model set up and results from the "extreme scenarios"can be found in Section 4 of the supplementary information.

5.1.Socioeconomic

Our assumptions for the socioeconomic development is based on the shared socioeconomic pathway SSP2 Middle of the Road (Fricko et al., 2016). The SSPs are global development pathways built by the climate change impact community to provide a context for scenarios of radiative forcing (RCPs) to be examined. The SSPs consider the challenges of mitigation and adaption to climate change. O'Neill et al. (2017) provide an overview of the qualitative narratives and direction of change for global drivers of development of each of the scenarios.

The quantification of the drivers of the SSPs that focus on the challenges associated with the socioeconomic development were conducted by demographers and modeling groups and provide insights into population and urbanization (Jiang and O'Neill, 2015; KC and Lutz, 2017) and economic growth (Crespo Cuaresma, 2015; Dellink et al., 2017; Leimbach et al., 2015).

In Fricko et al. (2016), the full quantification of SSP2 is presented using the quantified drivers and an impact assessment modeling framework which links the economic land use model GLOBIOM with an energy demand model MESSAGE. Embedded in this future pathway for SSP2 are the drivers and assumptions, which include: population growth, per capita income growth, intrinsic technical progress for livestock yields, crop yields, and irrigation application efficiencies.

Using alternative SSPs we tested the impacts of our irrigation investment strategies under several indicators. We chose *SSP1: Sustainability* and *SSP3: A Rocky Road* because they represented a plausible envelope of development that would be "better" and "worse" than SSP2. Table 4 provides an overview of the global and regional population and GDP drivers for the alternative SSPs. Population growth and the economic development of the region will have impacts on future food demand, as well as the region's investments and advancements in agricultural productivity. We use an econometric relationship of the per capita income and historical crop yields to estimate the intrinsic technological improvement in crop and livestock yields.

Table 4. Population, GDP and GDP per capita assumptions by region for SSPs

Region	Indicator	Unit		2050			2100		
			2010	**SSP1**	**SSP2**	**SSP3**	**SSP1**	**SSP2**	**SSP3**
MNA	Population	(billion people)	0.38	0.55	0.61	0.69	0.48	0.65	1.02
	GDP	(trillion USD 2005 MER)	1.86	8.38	7.69	6.69	16.56	18.78	12.38
	GDP per capita	(1000 USD 2005 MER)	4.88	15.14	12.54	9.66	34.82	28.79	12.09
AFR	Population	(billion people)	0.86	1.55	1.78	2.07	1.69	2.40	3.59
	GDP	(trillion USD 2005 MER)	0.84	8.85	6.36	4.44	52.73	46.61	19.34
	GDP per capita	(1000 USD 2005 MER)	0.98	5.71	3.58	2.15	31.13	19.42	5.39
EAP	Population	(billion people)	2.02	2.00	2.09	2.21	1.19	1.47	2.01
	GDP	(trillion USD 2005 MER)	6.05	39.69	30.26	22.92	45.33	43.56	25.80
	GDP per capita	(1000 USD 2005 MER)	2.99	19.83	14.45	10.38	38.08	29.66	12.86
ECA	Population	(billion people)	0.48	0.47	0.49	0.51	0.33	0.42	0.55
	GDP	(trillion USD 2005 MER)	2.83	9.39	8.27	6.80	13.05	14.79	9.90
	GDP per capita	(1000 USD 2005 MER)	5.92	20.12	16.91	13.40	39.37	35.21	17.99
LCR	Population	(billion people)	0.58	0.67	0.74	0.85	0.48	0.67	1.08
	GDP	(trillion USD 2005 MER)	3.19	12.30	10.35	8.61	22.56	23.98	15.08
	GDP per capita	(1000 USD 2005 MER)	5.46	18.24	13.96	10.09	46.59	35.79	13.97
NAM	Population	(billion people)	0.35	0.46	0.45	0.38	0.52	0.51	0.29
	GDP	(trillion USD 2005 MER)	14.29	33.69	29.93	24.75	56.42	46.59	23.70
	GDP per capita	(1000 USD 2005 MER)	41.05	72.79	66.10	65.94	108.02	90.50	80.84
ADP	Population	(billion people)	0.15	0.16	0.15	0.13	0.12	0.12	0.07
	GDP	(trillion USD 2005 MER)	5.55	10.48	8.79	6.82	15.81	13.21	5.54
	GDP per capita	(1000 USD 2005 MER)	36.21	67.00	58.38	52.86	126.62	106.47	75.85
SAR	Population	(billion people)	1.60	2.05	2.30	2.63	1.53	2.17	3.55
	GDP	(trillion USD 2005 MER)	1.48	14.65	10.90	7.52	36.88	35.23	15.97
	GDP per capita	(1000 USD 2005 MER)	0.92	7.15	4.74	2.86	24.06	16.23	4.50
EC	Population	(billion people)	0.41	0.47	0.46	0.39	0.45	0.45	0.26
	GDP	(trillion USD 2005 MER)	14.17	28.62	26.11	20.00	51.28	49.31	20.47
	GDP per capita	(1000 USD 2005 MER)	34.47	60.29	56.72	51.52	113.70	109.27	77.69

The changes in population and per capita GDP will also have an impact on water demand for domestic and industrial uses. Projections from the Water Futures and Solutions fast-track modeling effort which were used to model water demand from domestic and industrial/energy users for SSPs 1-3 (Wada et al. 2016). In our modeling approach, agriculture is the residual user of water, meaning demand for water for domestic and industry/energy takes priority over agriculture (Figure 25).

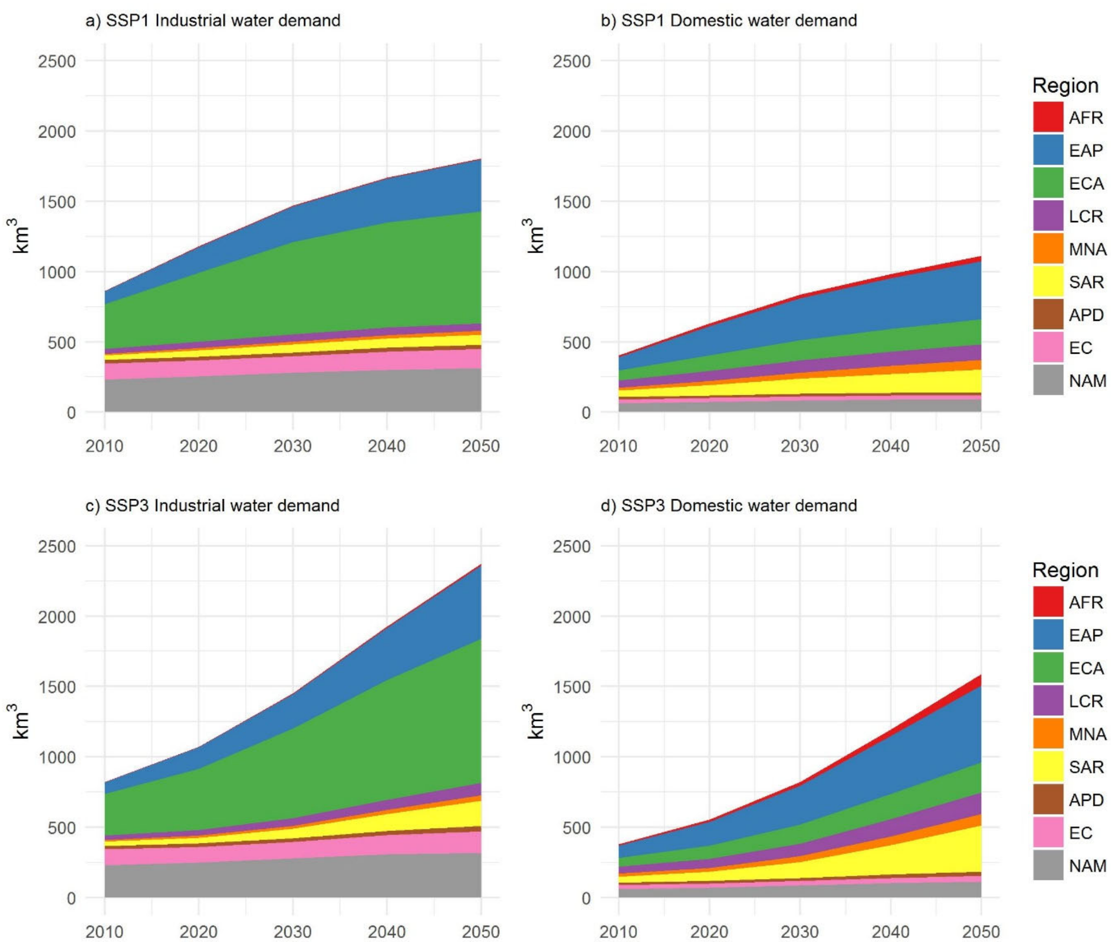

Figure 25. Water demand by domestic and industrial users by region from 2010-2050 from PCR-GLOBWB (Wada et al 2016) (km³).

By 2050, global population is expected to increase about 9 billion in SSP2, 8.4 billion in SSP1 and 9.9 billion in SSP3. By 2100, the differences are more far greater: 6.8 billion in SSP1, 8.9 billion in SSP2, and 12.4 billion in SSP3. Global average per capita GDP triples in SSP1, doubles in SSP2, but increases only 50% in SSP3 by 2050. The differences between SSPs are more dramatic on the regional level, especially in AFR and SAR. Both population and per capita GDP impact the demand for crop and livestock products.

Compared the differences between the total production under *MaxInvest* and *ZeroInvest* investment strategies, total production for SSP1 is the highest of all SSPs with most of the increase in production coming from EAP. With higher incomes in SSP1, calorie availability increases in nearly all the regions, especially in SAR and LCR compared to SSP2 and SSP3, though AFR and MNA see the largest increase in kilocalories for SSP3, due to changes in regional prices from the relative increase in regional production (Figure 27).

Water demand from other users increases 130% in SSP1, 182% in SSP2, and 229% in SSP4 by 2050 (Figure 25). Although competition for water for irrigation, domestic, and industrial users occurs at the grid level, the regional level offers insight into which regions will face the most competition for water. Demand for water from other users reduces the water left for agriculture, and in regions like EAP and SAR where the trade-offs between water demand for irrigation and other sectors can be seen (Figure 26).

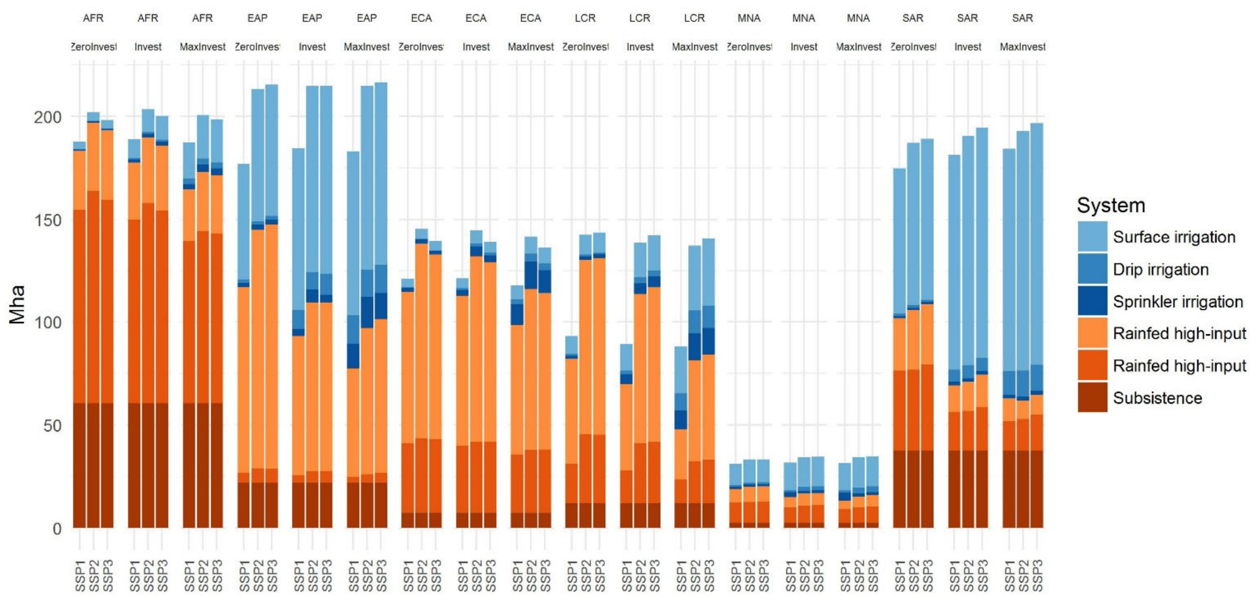

Figure 26. Cropland area by system under different socioeconomic conditions in 2050 under *ZeroInvest*, *Invest*, and *MaxInvest* by region (Mha)

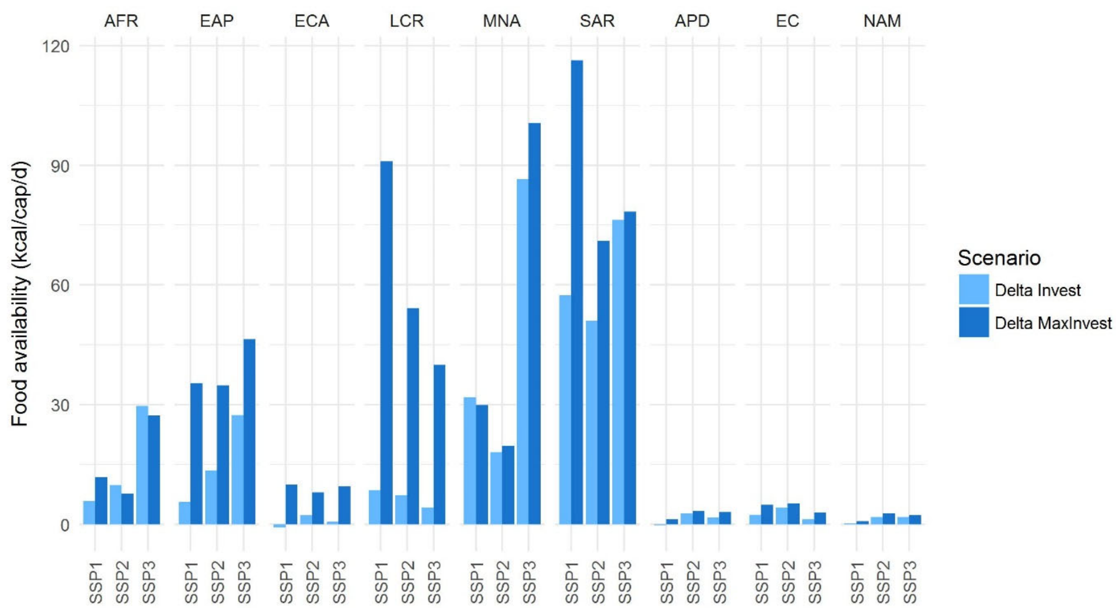

Figure 27. Change in food availability under different socioeconomic conditions in 2050 compared to *ZeroInvest* by region (kilocalorie per capita per day)

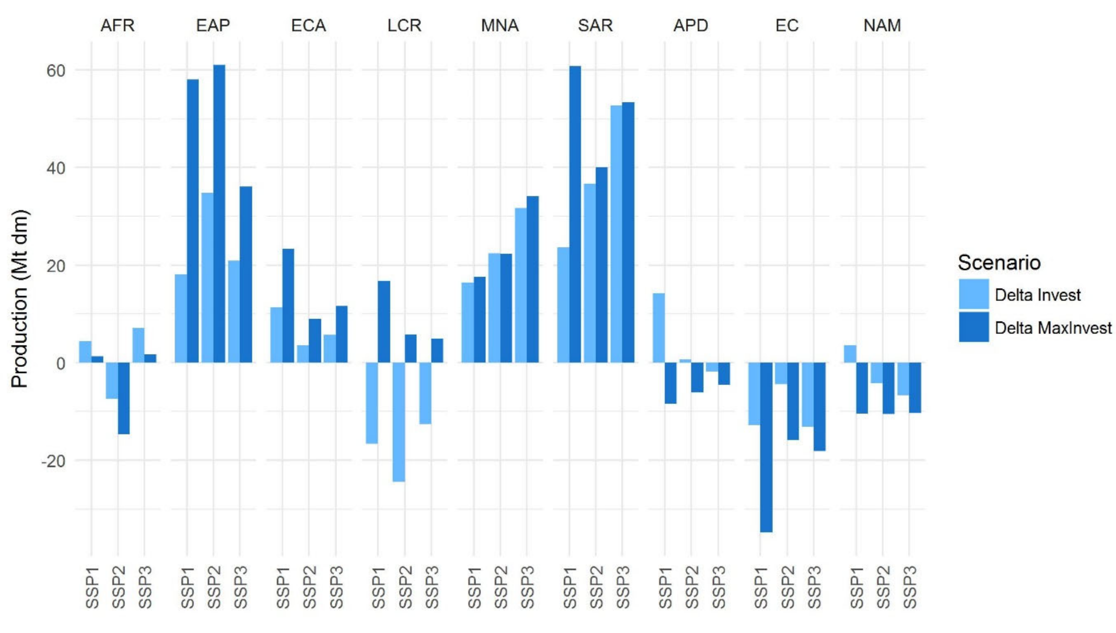

Figure 28. Change in crop production under different socioeconomic conditions in 2050 compared to *ZeroInvest* by region (Mt dm)

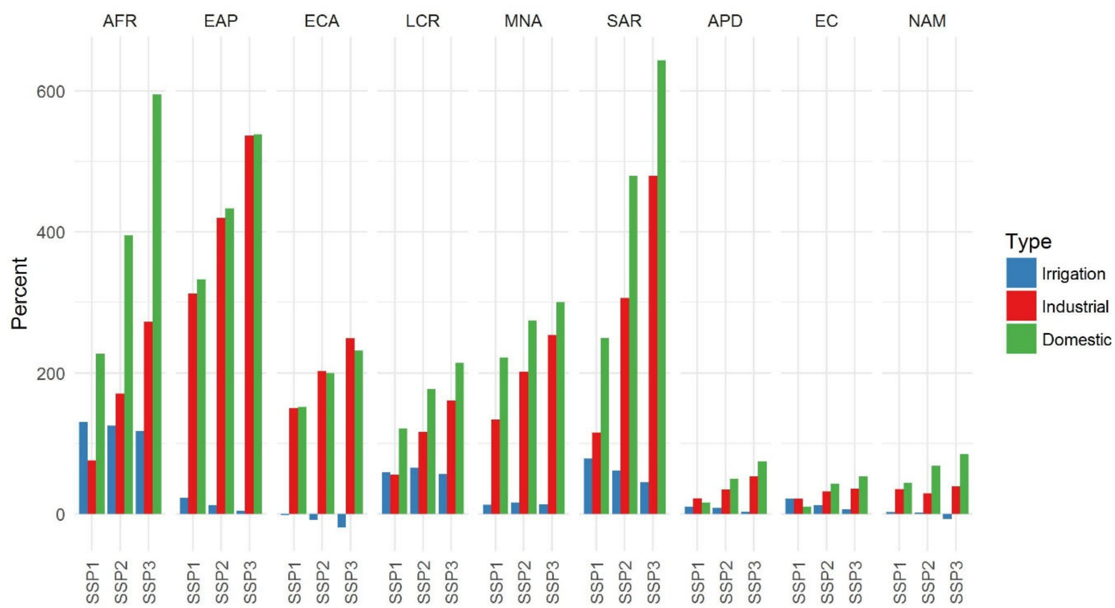

Figure 29. Relative differences in water demand by sector under *MaxInvest* compared to 2010 levels of water demand under different socioeconomic conditions (%)

Crop yields are much higher under the SSP1 sensitivity scenario and therefore less area (incl. irrigated area) is needed to provide the supply necessary to meet demand. As a result, irrigated area increases less under SSP1 than under SSP2 in all regions except for the Middle East and North Africa. The required investments are therefore also lower under SSP1 ($894 billion for *Invest* scenario, a difference of $183 billion; $1,666 billion for the *MaxInvest* scenario, a difference of $336 billion) (Figure 30).

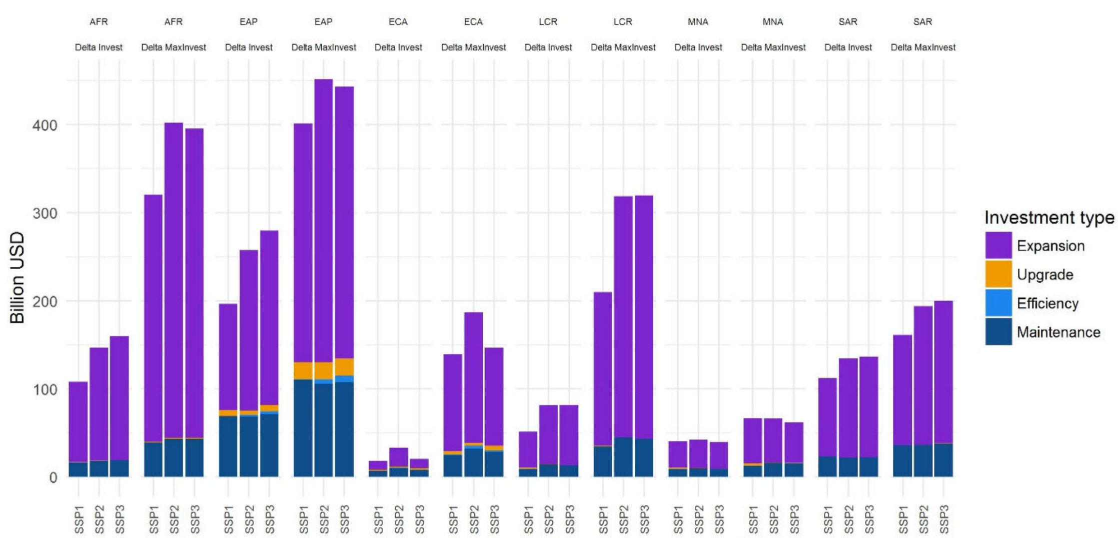

Figure 30. Difference in cumulative developing country investment costs for *Invest* and *MaxInvest* scenarios from (up to 2050) under different socioeconomic assumptions compared to *ZeroInvest* ($ billion, 2000 US dollar)

5.2.Climate impacts

Climate change is considered to be a major challenge for agricultural production. The potential impacts on productivity of crops under heat and water stress can be simulated using globally gridded crop models (GGCM) that simulate the effects of increased radiative forcing from general circulation models (GCMs) on temperature, precipitation, and nutrient requirement. Changes in precipitation due to changes in radiative forcing also impact future annual and monthly stream flows which in turn impact water available for irrigation.

Climate change impacts are modeled using the bias-corrected climate datasets produced by the five general circulation models (GCMs) (Table 5) (HadGEM2-ES, IPSL-CM5A-LR, GFDL-ESM2M, MIROC-ESM-CHEM, NorESM1-M) available from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP)[7] and used in also used in Phase 5 of the Coupled Model Intercomparison Project (CMIP5),[8] which offers a framework to compare climate impact projections in different sectors and at different scales (Warszawski et al., 2014). The GCMs are combined with different levels of atmospheric CO_2 concentrations as prescribed by the RCPs (RCP 8.5 and RCP 2.6) to reveal the impact of climate change on global changes in temperature and precipitation. Although, the scientific community has yet to reach an agreement on whether the potential benefits from increased CO_2 can be taken up and used by crops, especially if temperature and precipitation reduce crop yields, the impacts of CO_2 fertilization on crop yields can be modeled with the globally gridded crop model EPIC (Environmental Policy Integrated Climate model). EPIC uses these changes in temperature, precipitation, and atmospheric CO_2 concentration to model the impacts on crop yields, nutrient and water requirement for each to the GCMs and RCPs. The impacts of carbon fertilization are also excluded from the crop yield impacts for one of the GCMs (HadGEM2-ES). These data sets are provided by the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2011).

Table 5. General Circulation Models (GCMs) used to project climate change

GCM	Modeling group	Country
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	USA
HadGEM2-ES	Met Office Hadley Centre	UK
IPSL-CM5A-LR	Institut Pierre-Simon Laplace	France
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	Japan
NorESM1-M	Norwegian Climate Centre	Norway

Source: Coupled Model Intercomparison Project Phase 5 (https://cmip.llnl.gov/cmip5)

GLOBIOM has been used for assessments of agriculture under future climate change that considered impacts of alternative adaptation strategies (Leclère et al., 2014) and the role of trade (Mosnier et al., 2014) to mitigate the impacts of climate. While the climate effects on grassland productivity are less studied than those effects on crop productivity, GLOBIOM has included these impacts to understand the economic and land use implications (Wheeler and Reynolds, 2012; Havlík et al., 2015).

For this sensitivity analysis, we have used the crop modeling simulations produced with EPIC and considered the most extreme radiative forcing (RCP 8.5), general circulation model (HadGEM GCM),

[7] https://www.isimip.org
[8] https://cmip.llnl.gov/cmip5

and have also considered both increased CO_2 fertilization effect and no CO_2 fertilization effect, to show the potential range of the biophysical and economic impacts on crop yields and input requirement due to climate change. Elliot et al. (2014) estimate that climate impacts could reduce currently irrigated areas by 20-60 Mha, however these impacts only become significant after 2070. Elliot et al.(2014) and Konzmann et al. (2013) find that increased CO_2 concentrations may, on average, decrease irrigation water consumption due to the shorter growing period and changes in precipitation in some regions. Impacts are applied globally using the relative changes in the globally-gridded crop models yields from 2000 (Nelson et al., 2010; 2014a, 2014b; von Lampe et al., 2014).

Climate impacts on surface water availability were simulated with the Lund-Potsdam-Jena managed land model (LPJml), which is a global dynamic vegetation model which models water and carbon cycles (Bondeau et al., 2007; Gerten et al., 2004). The model used the temperature, precipitation and radiative forcing levels (RCP 8.5) from HadGEM to simulate the impacts of climate change on precipitation and discharge were aggregated at the monthly level to simulate the change in surface water availability.

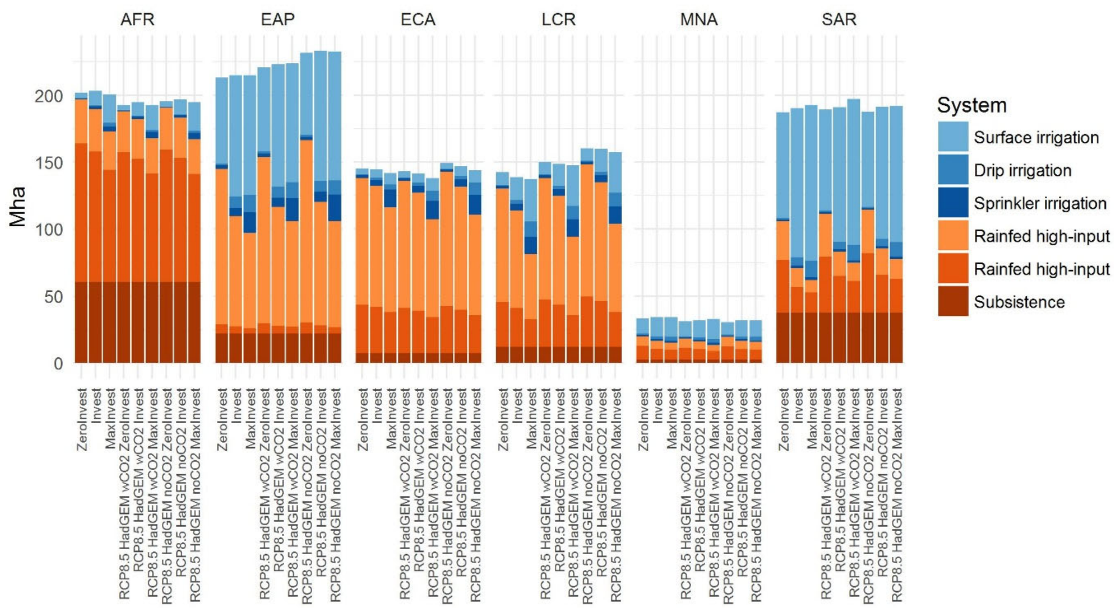

Figure 31. Cropland area by systems under different future climates in 2050 under *ZeroInvest*, *Invest*, and *MaxInvest* compared by region (Mha)

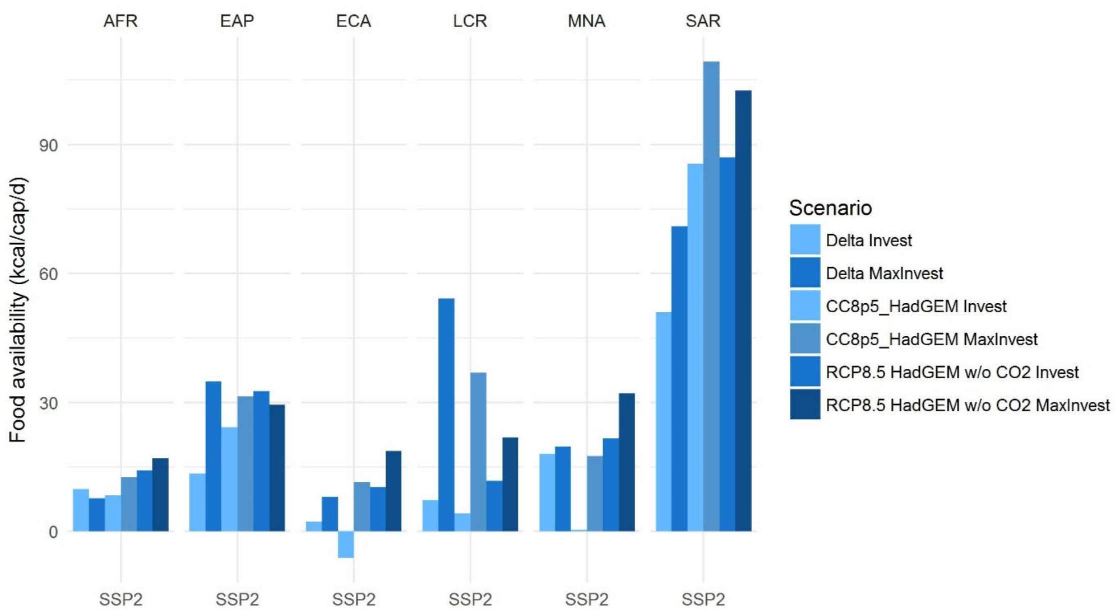

Figure 32. Change in food availability (kcal/cap/day) under different future climates in 2050 compared to *ZeroInvest* by region

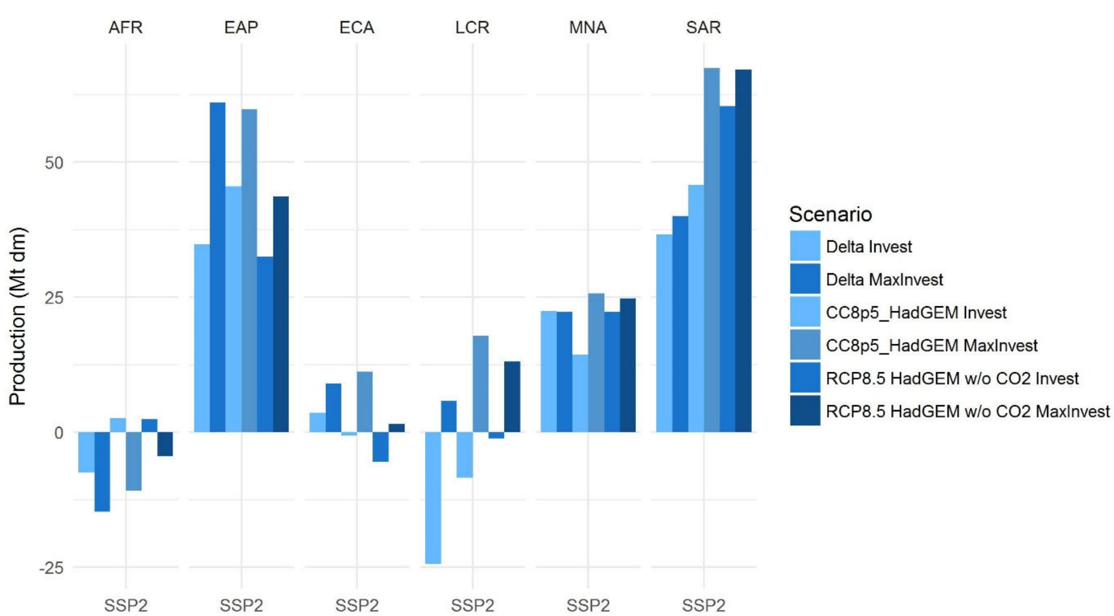

Figure 33. Change in production under different future climates in 2050 compared to *ZeroInvest* by region (Mt dm)

Investment costs under future climates are influenced by two effects operating simultaneously. The first is the rise in temperatures which has a negative effect on crop yields. In order to compensate for the decline in crop production, this creates pressure on crop area to be higher under future climates. In the case of irrigated area, however, this effect is moderated by lower irrigation water availability, meaning that area expansion occurs primarily in rainfed systems. In the most negatively affected regions, this results in irrigation investment costs being lower under future climates than under *Invest*, *MaxInvest*, and *ZeroInvest* scenarios. The negatively affected regions are generally those in the lower latitudes (AFR, LCR, MNA, and SAR). In contrast, higher latitude areas (EAP, ECA, and NAM) see higher irrigated area expansion and higher investment costs under future climates. Total developing country investment costs under future climate in the *Invest* scenario are $1.06 trillion from 2010 to 2050, or $20 billion less than under current climate. In the *MaxInvest* scenario, developing country costs under future climates are $1.93 trillion from 2010 to 2050, or $68 billion less.

The removal of the CO_2 fertilization assumption from future climates generally depresses yields even further creating more pressure on area expansion. Under *Invest* with no CO_2 fertilization, total developing country costs are $1.14 trillion, or $80 billion more than with CO_2 fertilization. Under *MaxInvest*, total developing country costs are $2.07 trillion, or $140 billion more than with fertilization. In terms of investment costs, global effects of CO2 fertilization are therefore larger than the effects of future climate scenarios themselves. There are varying changes to investment costs at the regional level, driven by differences between regions in yield changes of individual crops.

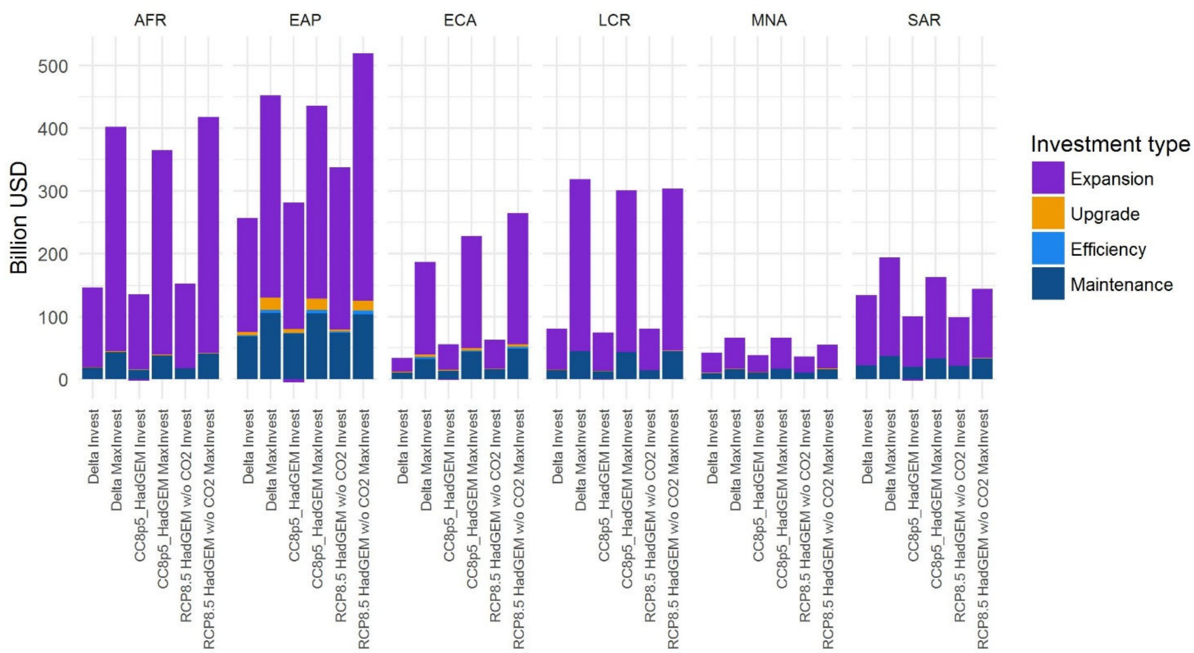

Figure 34. Difference in cumulative developing country investment costs under different future climates compared to *ZeroInvest* in 2050 by region ($ billion, 2000 US dollar)

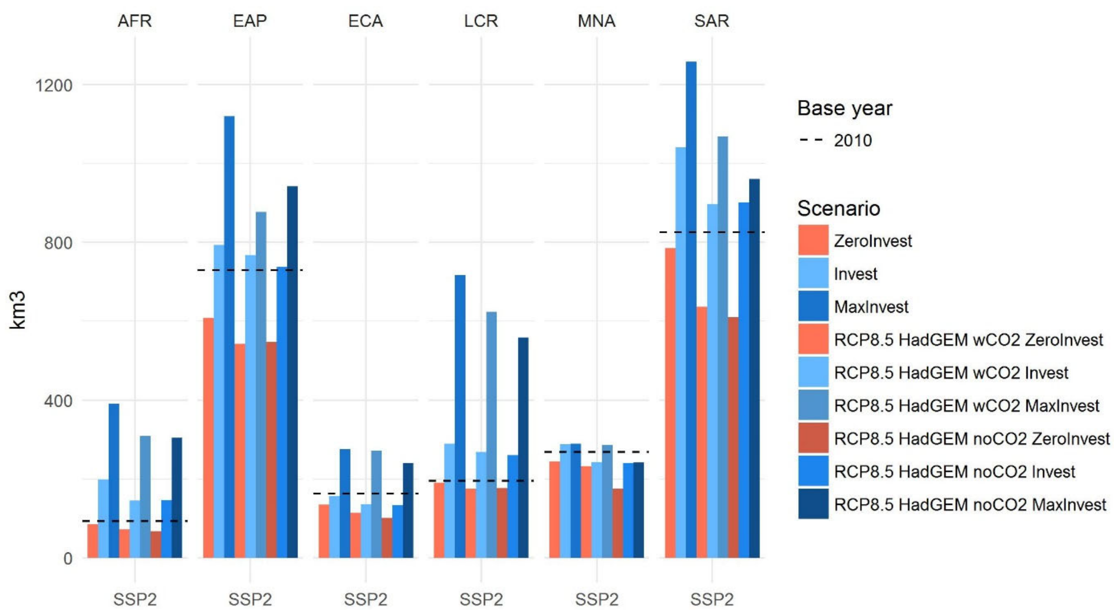

Figure 35. Water withdrawal for irrigation under different future climates in 2050 by region (km^3)

5.3. Dietary

Evolution of future diet will have large impacts on future demand for cropland and pasture and therefore impact irrigation needs. In the SSP2 scenario, we assume an evolution of diets in line with FAO projections (Alexandratos and Bruinsma, 2012). These diets assume continuation of dietary transitions in developing countries, in particular with increase of animal product consumption driven by economic growth.

In our sensitivity analysis, we look at the irrigation development impacts under two different diet scenarios. Under the "healthy diet" scenario, we are considering some evolution of diets towards lower meat intake in developed countries and a catching up of developing regions suffering from undernourishment. This scenario is based on the assumption of the SSP1 narrative (Fricko et al., 2017), and also considers more sustainable consumption patterns with lower domestic waste. Globally, consumption increases from 2,896 kcal/cap/day in the model in 2010 to 3,283 kcal/cap/day, with all developing regions above 3,000 kcal/cap/day. In contrast, for SSP2, South Asia remains at 2,935 kcal/cap/day in 2050 and Sub-Saharan Africa is about 120 kcal/cap/day lower than in SSP1, in spite of global consumption reaching a higher level at 3,311 kcal/cap/day by 2050. Animal product consumption is notably decreased in the Healthy Diet scenario for developed regions (-17% in North America, -20% in Western Europe, -24% in Pacific Developed regions). However, heathier diets in developing regions compensate this decrease and the global level of meat consumption remains comparable at about 460 kcal/cap/day.

A second diet scenario, "Healthy and Sustainable diet", considers one level further in terms of dietary change ambition. In that scenario, all large meat consumer regions are cutting their consumption in order to decrease their diet GHG emission footprint. Cuts are implemented for most developed countries and for the BRICS (Brazil, Russia, India, China and South Africa), and protein deficits are compensated through an increase in consumption of vegetable products. Under that scenario, average animal consumption decreases by 25% by 2050 compared to the SSP2 level, although Sub-Saharan Africa and South Asia still increase their consumption of animal meat for reaching healthy nutrient consumption levels. In North America and Western Europe, the decrease of animal products reaches 50% of the initial consumption level in 2010.

The role of varying dietary changes on the irrigation investment need and related costs is illustrated in the figures below, showing the impact of moving to "Healthy Diet" or "Healthy and Sustainable Diet" on the *Invest* and *MaxInvest* investment scenario results.

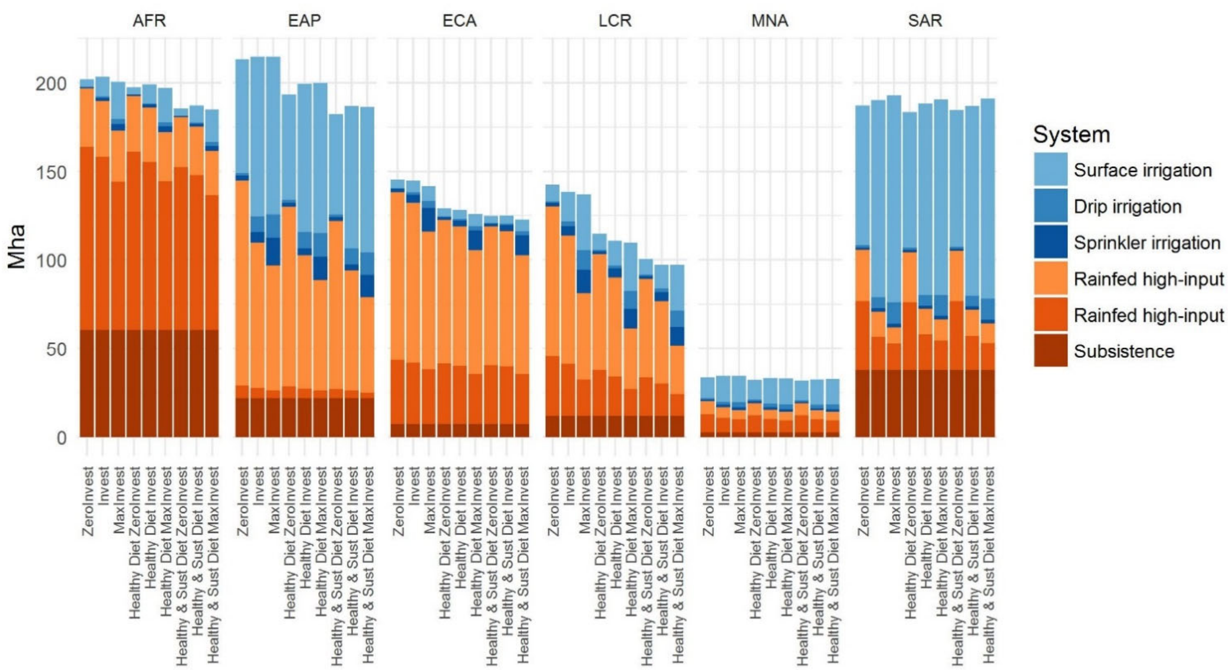

Figure 36. Cropland area by system type under different dietary patterns under *ZeroInvest*, *Invest*, and *MaxInvest* by region in 2050 (Mha)

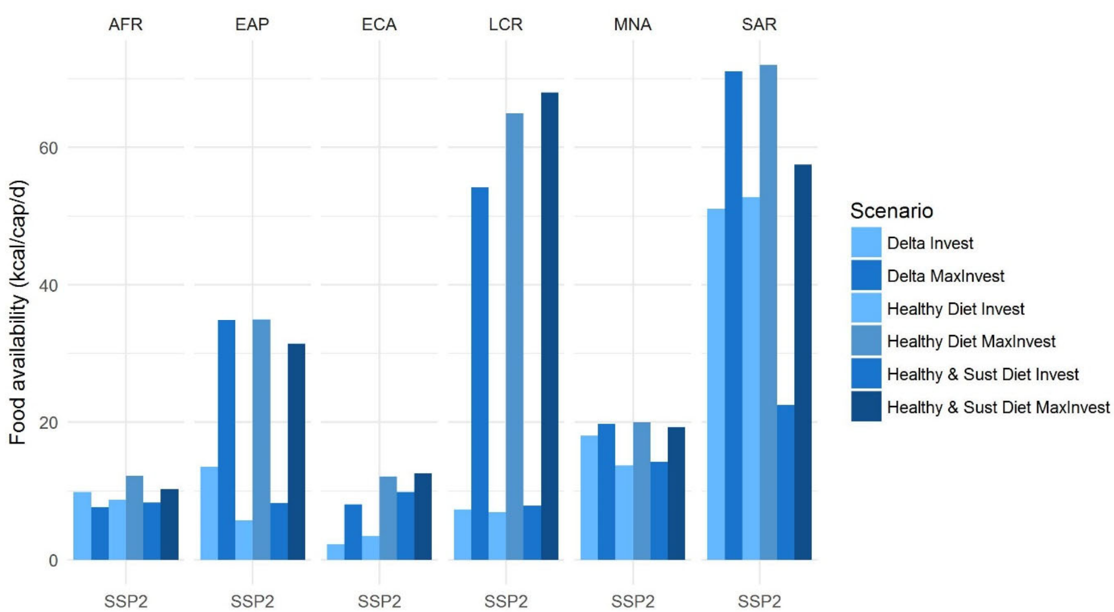

Figure 37. Change in calorie availability per capita per day under different dietary patterns difference from *ZeroInvest* in 2050 by region (kcal/cap/day)

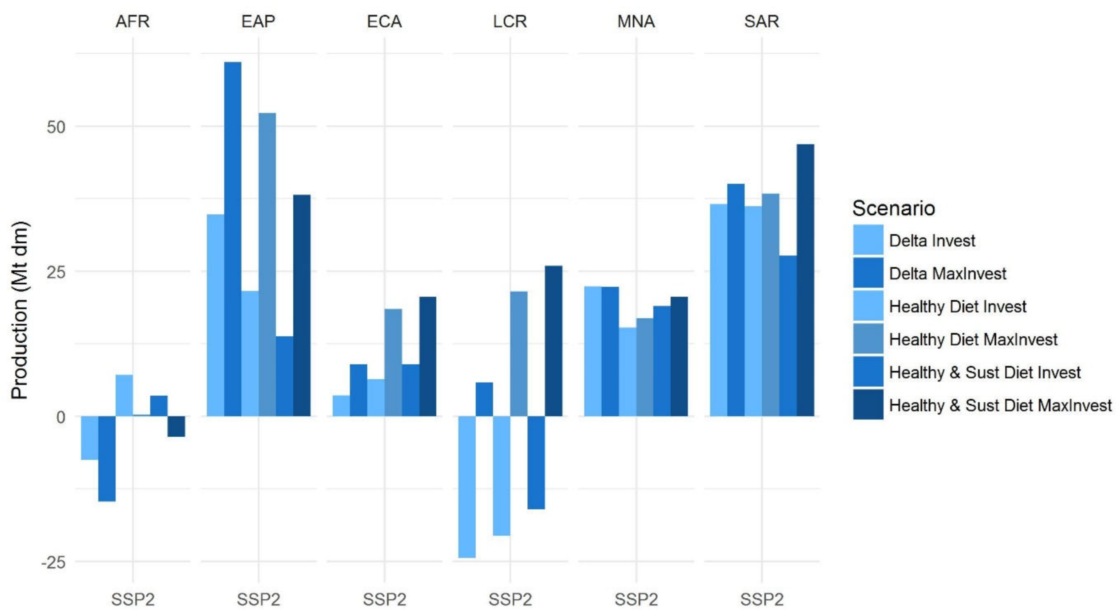

Figure 38. Change in crop production under dietary patterns compared to *ZeroInvest* in 2050 by region (Mt dm)

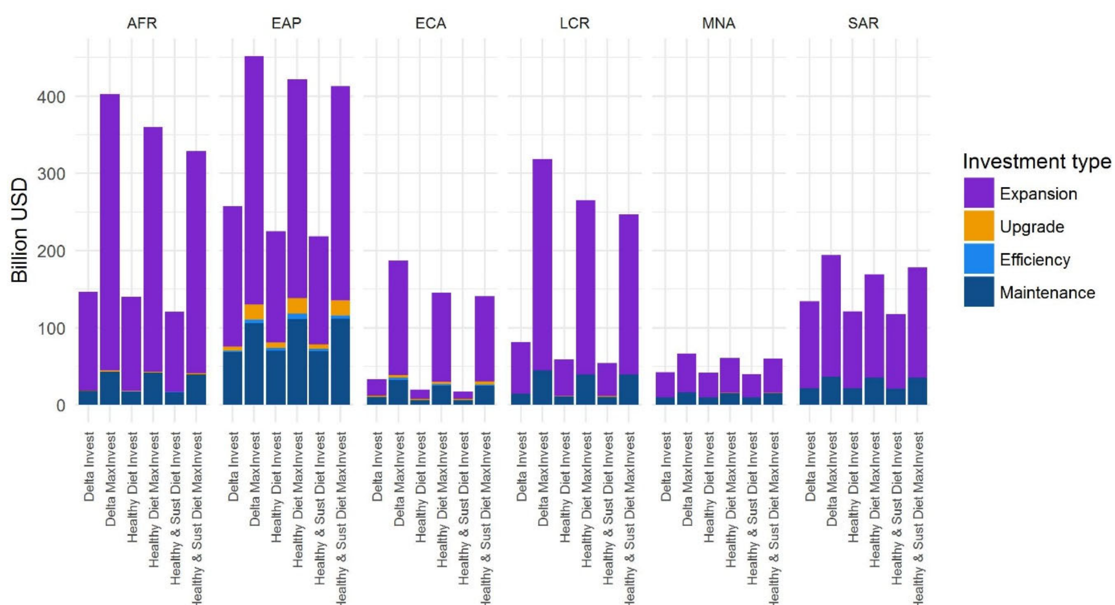

Figure 39. Difference in cumulative developing country investment costs under different dietary patterns compared to *ZeroInvest* in 2050 by region ($ billion, 2000 US dollar)

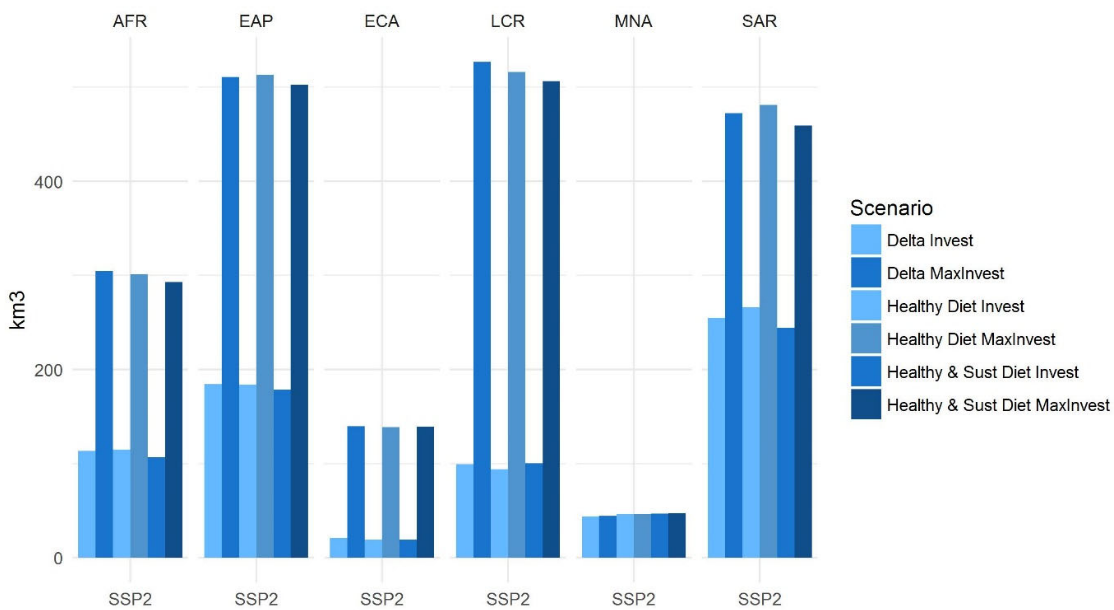

Figure 40. Change in water demand under dietary patterns compared to *ZeroInvest* in 2050 by region (km^3)

5.4. International trade

Sensitivity analyses are also performed on the trade response. Shocks in the agricultural supply chain that stem from conflicts or climate change can have profound effects and limitations on trade which can impact food security (Baldos and Hertel, 2015; Mosnier et al., 2014; Simson and Tang, 2013; van Dijk, 2011). We consider for this purpose two contrasted assumptions based the Shared Socioeconomic Pathways implementation in GLOBIOM. In the "Open Trade" scenario, we set the same trade assumptions as in SSP5, where trade elasticities are increased by 50% to represent much lower international transaction costs. In the "Restricted trade" scenario, transaction costs are on the contrary increased, to reflect barriers to trade and elasticities are decreased by 50%. The impact of varying international trade assumptions can be seen in the figures below.

EAP has less imports (more irrigated area and production) under the open trade assumptions as compared to the restricted trade assumptions. ECA and LCR, which were net exporters in 2050 in *Invest*, *ZeroInvest*, and *MaxInvest*, export more (using more irrigated area and increasing production) under the open trade assumptions as compared to the restricted trade assumptions. MNA and SAR, which were net importers in 2050 in *Invest*, *ZeroInvest* and *MaxInvest*, import less (using more irrigated area and increasing production) under the restricted trade assumptions compared to the open trade assumptions. AFR which is a net importer in almost all scenarios, the results are less straightforward. AFR imports less under the open trade scenarios and uses more irrigated area, but at the same time produces less. This could also be due to the change in the kinds of crops produced in the trade scenarios.

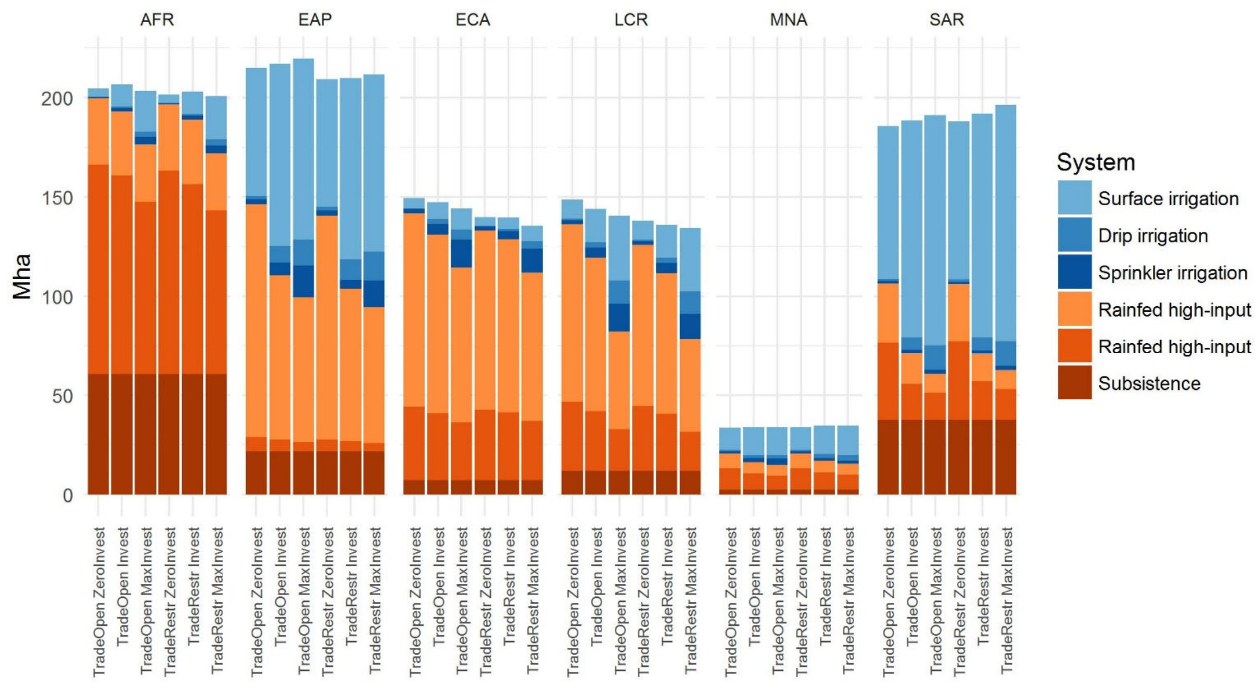

Figure 41. Cropland area by system under different international trade assumptions under *ZeroInvest*, *Invest*, and *MaxInvest* by region in 2050 (Mha)

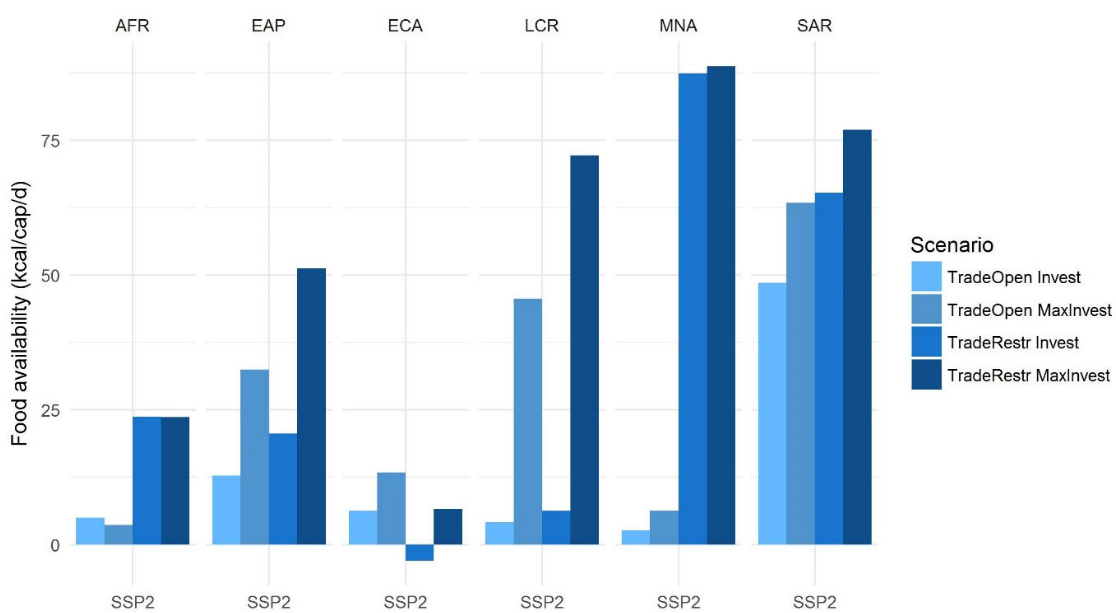

Figure 42. Change in food availability under different international trade assumptions compared to *ZeroInvest* in 2050 by region (kilocalorie per capita per day)

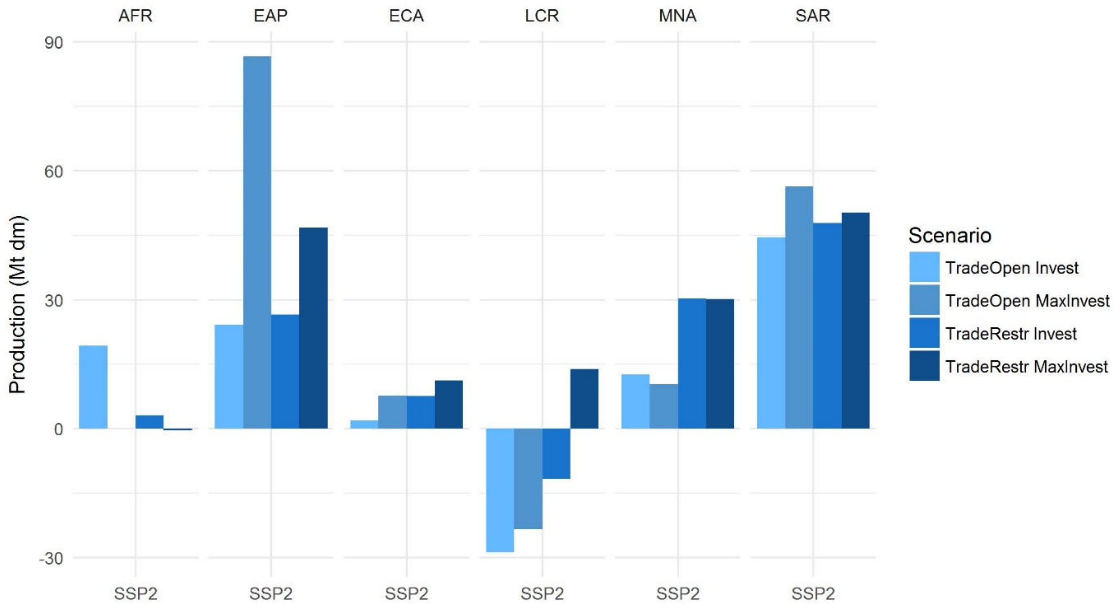

Figure 43. Change in crop production under different international trade assumptions compared to *ZeroInvest* in 2050 by region (Mt dm)

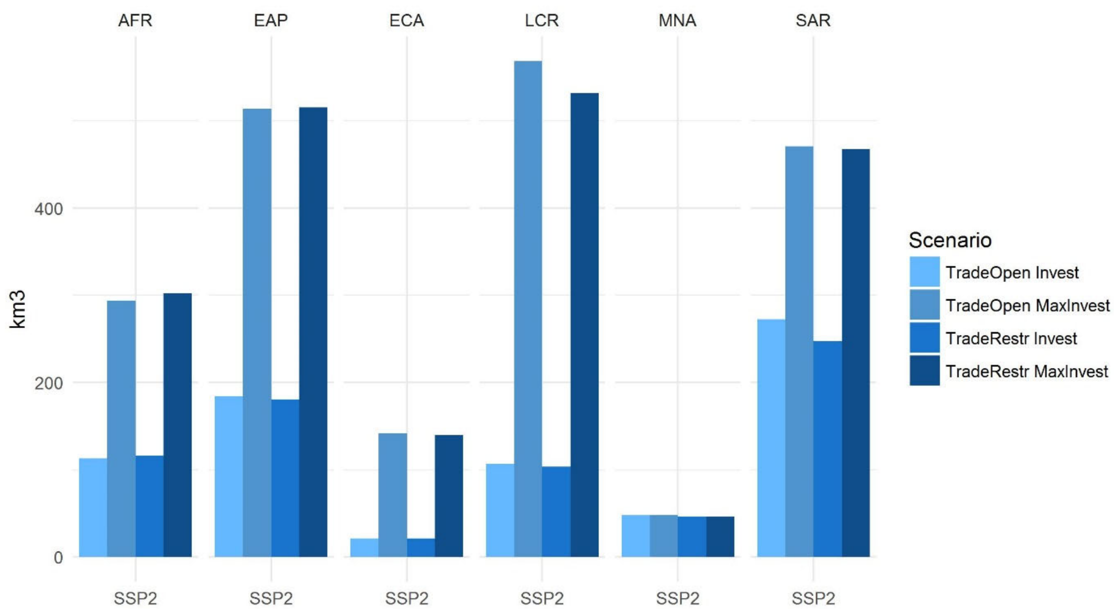

Figure 44. Change in water demand under different international trade assumptions compared to *ZeroInvest* in 2050 by region and scenario (km^3)

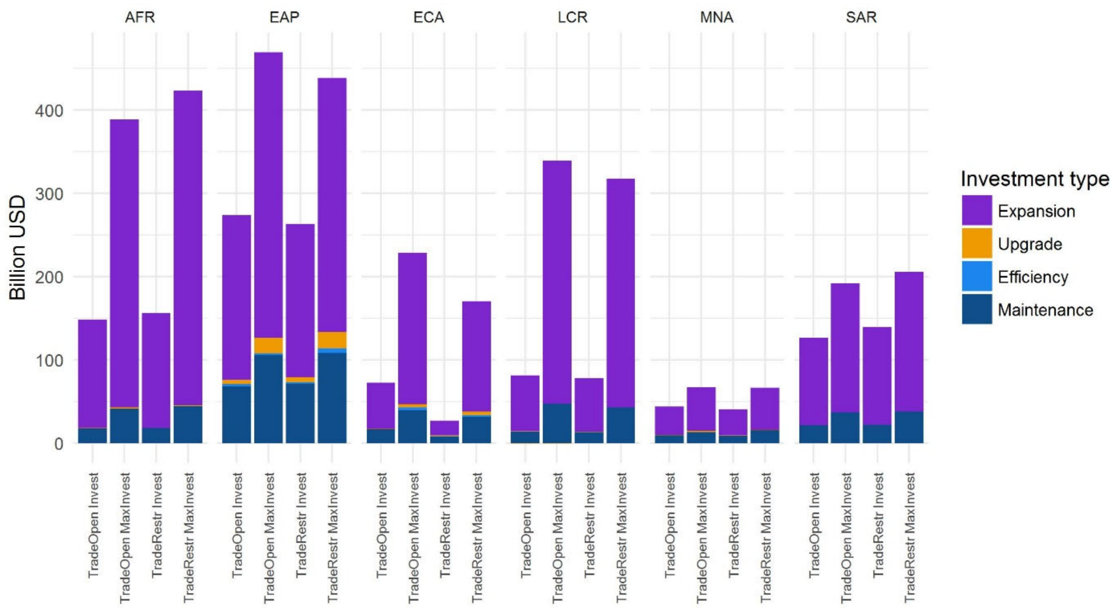

Figure 45. Difference in cumulative developing country investment costs under different international trade assumptions compared to *ZeroInvest* by region ($ billion, 2000 US dollar)

5.5. Water application efficiency

In our analysis, we use water application efficiency (WAE) as an indicator of the productivity of water. WAE provides us with a measure of the on the "crop per drop" impacts of irrigation investments that not only expand irrigated area but also upgrade irrigated area over time. Improvements in the WAE may will spare water for alternative human demands and reserve water for the environment. The efficiency scenarios are based on Hanasaki et al. (2013) who quantified the SSPs water sector assumptions using some of the socioeconomic narrative to derive drivers such as water application efficiency of irrigation. We used these assumptions on annual water application efficiencies to calibrate the scenarios in (Table 6).

Table 6. Sensitivity and baseline scenario assumptions for the water application efficiency (WAE) improvements per decade (%)

	WAE improvement per decade			
	0%	**1.5%**	**3.0%**	**5.0%**
Baseline scenarios	*ZeroInvest*	*Invest*	*MaxInvest*	
Sensitivity Scenarios	SSP3 low water efficiency scenarios[9]	SSP2 climate, diet , and trade scenarios	SSP1	high water efficiency scenarios[10]

We assume that the efficiency can be performed either through upgrading existing irrigation infrastructure, expanding irrigation infrastructure directly into more efficient systems (which would increase average efficiency of the region) or through increasing the efficiency of the inefficient systems

[9]Called LowWatrEff in the figures.
[10]Called HighWatrEff in the figures.

such as improvements to region's basin and furrow irrigation systems. Efficiency improvements can be achieved through improvements made to existing flood/gravity irrigation systems through land levelling, better irrigation scheduling, or improved water distribution (Miao et al., 2018), whereas upgrade improvements are achieved by converting existing irrigated areas from low efficiency systems (such as flood/gravity systems) to more efficient systems (such as drip and sprinkler systems). These efficiency costs are needed in EAP where upgrading the existing basin and furrow irrigation systems to sprinkler and drip is impractical given that the region grows predominately rice.

Achieving an increase in water efficiency for irrigation requires additional investment, either from upgrading systems or by improving overall efficiency of a system. These costs are not incurred in scenarios such as WaterEff_Low since there is no improvement in efficiency. In each scenario the irrigation costs are not fixed (only the unit costs are fixed).

Evans and Sadler (2008) describe the methods by which irrigation efficiency improvements can be achieved: crop selection, land retirement, deficit irrigation, and water application efficiency increase. Many of these methods are endogenous behaviors within GLOBIOM that allows for the selection of appropriate crops and conversion and reversion of cropland to maximize profits. There are of course some risks associated with increasing the efficiency of irrigation systems that shift to less flexible production systems (Adamson and Loch, 2014). However, when faced with increasing water scarcity, the practice of using deficit irrigation (irrigating less area and leaving the rest of the land for rainfed area) can be used as a coping strategy even in locations with highly efficient irrigation systems (English and Raja, 1996; Palazzo and Brozović, 2014). Deficit irrigation with respect to water-stress and impact on crop yields requires future analysis.

Return flows are not currently modeled within GLOBIOM and increasing the efficiency of irrigation may have significant impacts on how these return flows are re-distributed throughout a basin (Grafton et al., 2018). Stronger coupling between hydrological models and GLOBIOM in future analyses may allow for the feedbacks of return flows to be captured.

The impact of varying water application efficiency assumptions can be seen in the figures below. In 2050, crop production under *MaxInvest* with higher efficiency increases global production by 0.17%, and in MNA by 2% and in SAR by 1%. Grafton et al. (2018) discuss the incentives for increasing water extraction due to the improvements in irrigation efficiency. No efficiency improvement reduces production by about the same amount. In the *ZeroInvest* scenarios, the pattern is similar. There are very small increases in calorie availability under the high efficiency scenarios and overall less water demanded.

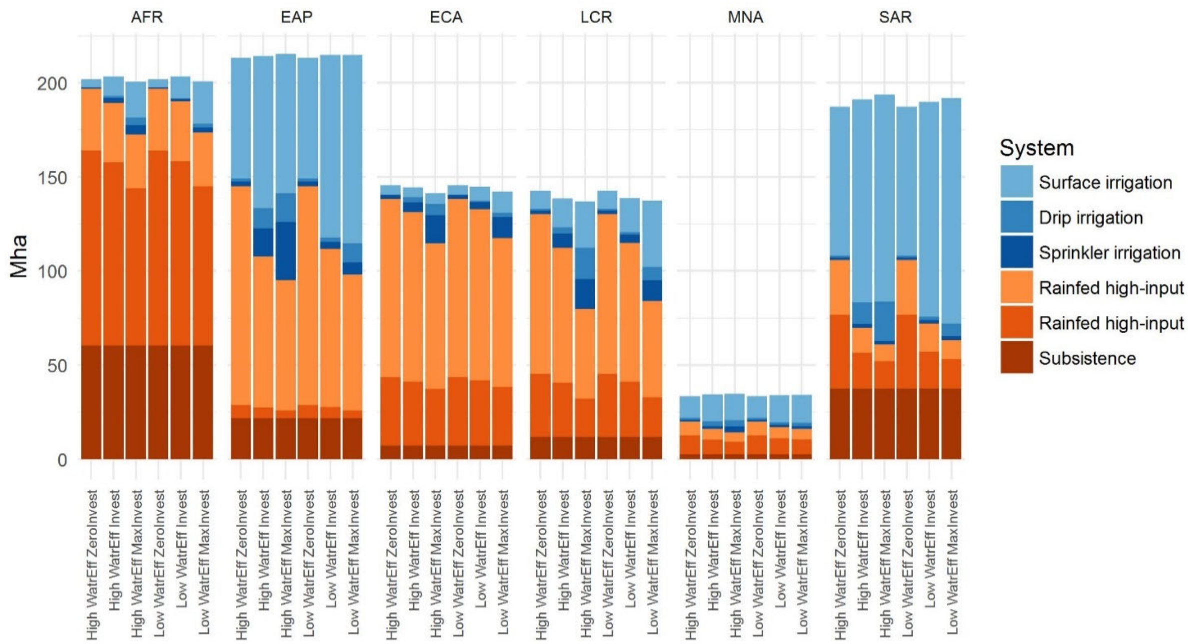

Figure 46. Cropland area by system under different irrigation application efficiency assumptions under *ZeroInvest*, *Invest*, and *MaxInvest* by region in 2050 (Mha)

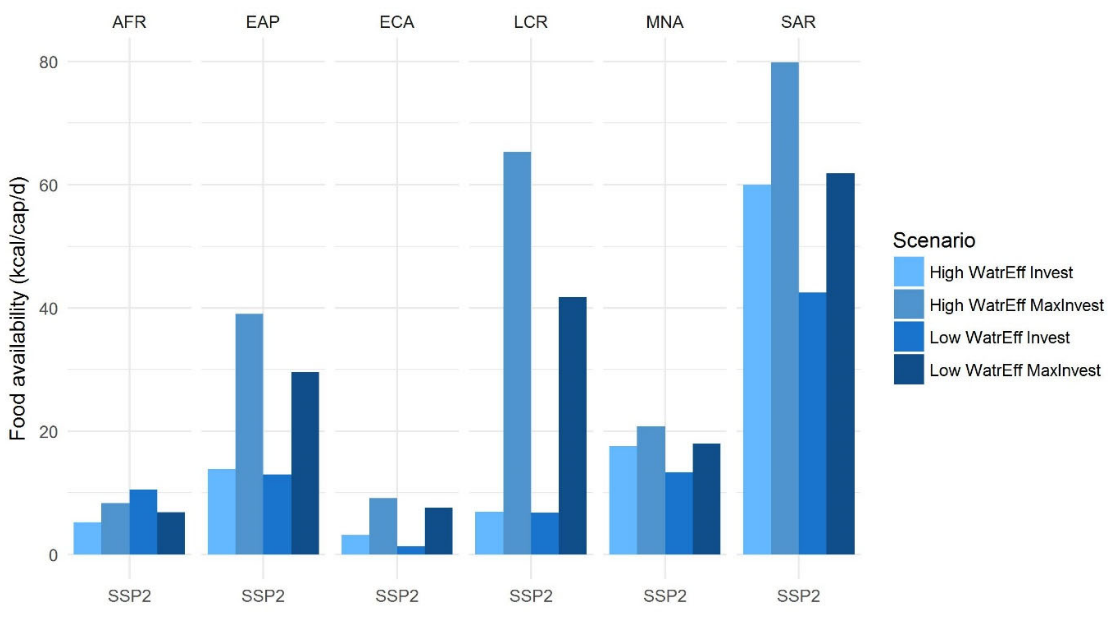

Figure 47. Change in food availability under different irrigation application efficiency assumptions compared to *ZeroInvest* in 2050 (kilocalorie per capita per day)

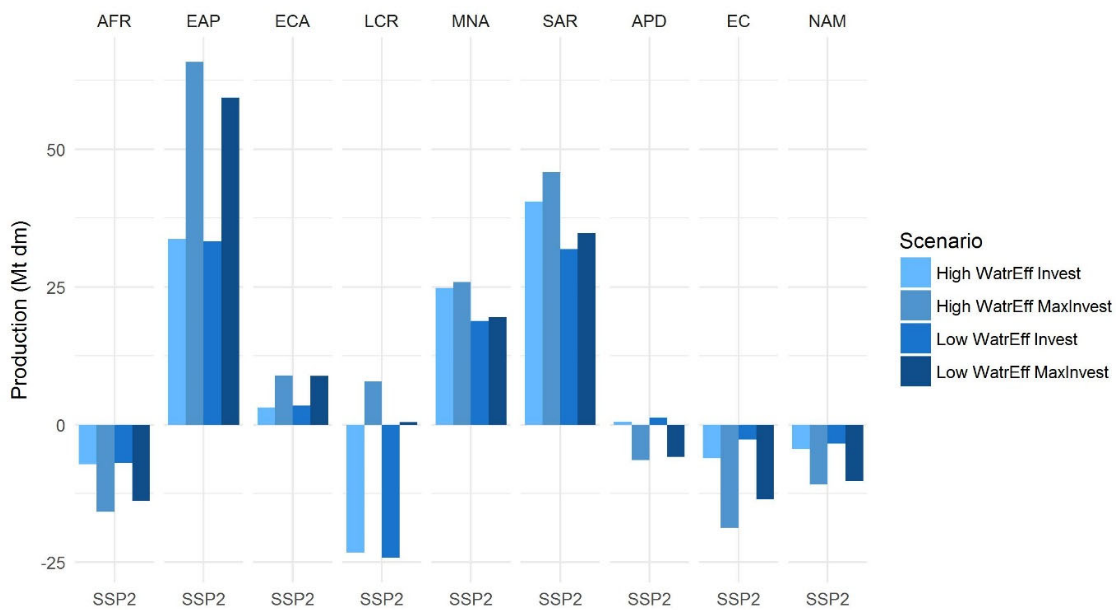

Figure 48. Change in crop production under different water application efficiency assumptions compared to *ZeroInvest* in 2050 by region (Mt dm)

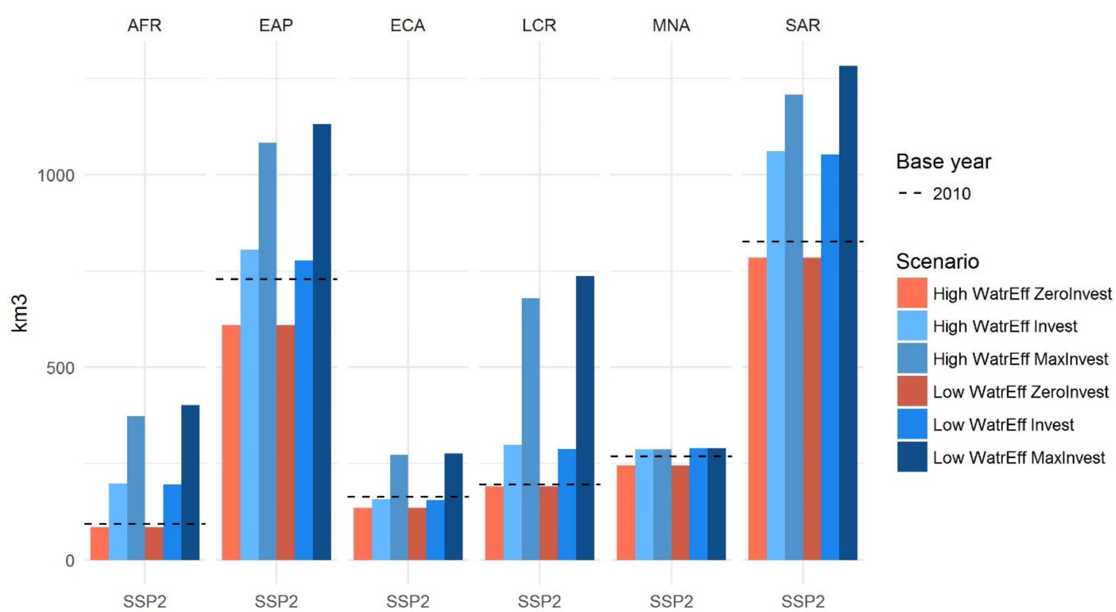

Figure 49. Water withdrawal for irrigation under different irrigation application efficiency assumptions in 2050 by region (km^3)

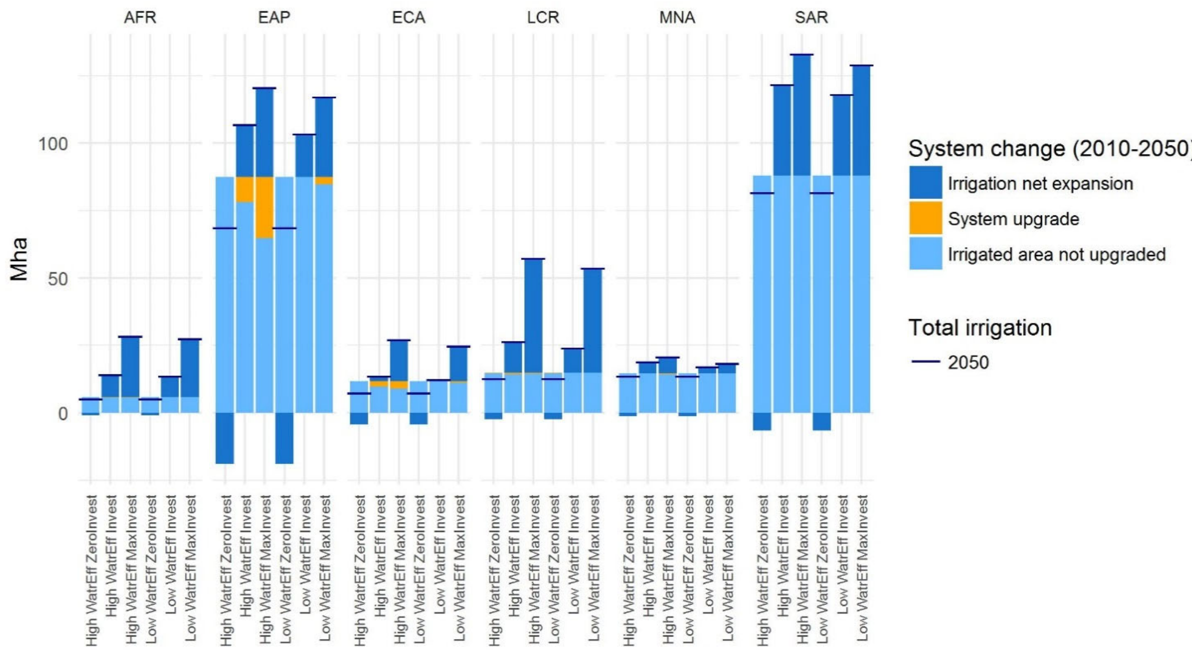

Figure 50. Cumulative irrigated area expansion and upgrade under various efficiency scenarios from 2010 to 2050 (Mha)

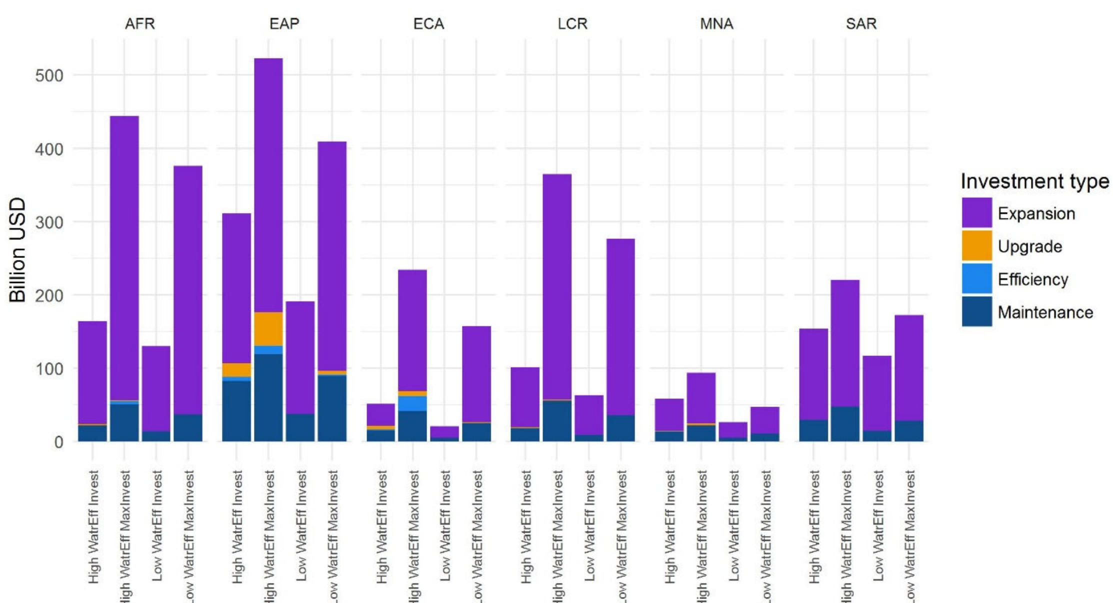

Figure 51. Difference in cumulative developing country investment costs under different water application efficiency assumptions compared to *ZeroInvest* in 2050 by region ($ billion, 2000 US dollar)

Tables 7 and 8 summarize the spread of investment costs under the sensitivity scenarios. Generally, shifting to higher efficiency irrigation systems and significant climate impacts, such as those from RCP 8.5 increases the investment costs. Sustainable consumption and weaker climate impacts such as those from RCP 2.6 decrease the irrigation investment requirement.

Table 7. Maximum and minimum difference in the cumulative irrigation investment costs of the sensitivity scenarios compared to baseline investment scenarios by region

	MaxInvest				Invest			
	Minimum difference in irrigation investment costs compared to *MaxInvest* 2050 (%)		Maximum difference in irrigation investment costs compared to *MaxInvest* 2050 (%)		Minimum difference in irrigation investment costs compared to *Invest* 2050 (%)		Maximum difference in irrigation investment costs compared to *Invest* 2050 (%)	
Region								
AFR	RCP2p6 NOR	-50%	WatrEff High	9%	HealthySustDiet	-14%	WatrEff High	9%
EAP	RCP2p6 NOR	-18%	WatrEff High	9%	WatrEff Low	-11%	RCP8p5 IPSL	12%
ECA	RCP2p6 NOR	-55%	RCP8p5 HadGem noCO2	33%	HealthySustDiet	-23%	TradeOpen	56%
LCR	RCP2p6 NOR	-60%	WatrEff High	12%	HealthySustDiet	-22%	WatrEff High	16%
MNA	RCP2p6 NOR	-26%	WatrEff High	21%	RCP2p6 NOR	-21%	WatrEff High	16%
SAR	RCP8p5 HadGem noCO2	-18%	WatrEff High	8%	RCP8p5 HadGem noCO2	-16%	WatrEff High	7%
WLD	RCP2p6 NOR	-28%	WatrEff High	10%	WatrEff Low	-9%	RCP8p5 IPSL	14%

Table-8. Maximum and minimum difference in the irrigated area of the sensitivity scenarios compared to baseline investment scenarios by region

	MaxInvest				Invest			
	Minimum difference in irrigated areas compared to *MaxInvest* 2050 (%)		Maximum difference in irrigated areas compared to *MaxInvest* 2050 (%)		Minimum difference in irrigated areas compared to *Invest* 2050 (%)		Maximum difference in irrigated areas compared to *Invest* 2050 (%)	
Region								
AFR	RCP2p6 NOR	-17%	WatrEff High	5%	RCP8p5 NOR	-23%	WatrEff High	5%
EAP	RCP2p6 NOR	-46%	TradeRestr	5%	HealthySustDiet	-11%	SSP3	5%
ECA	SSP1	-10%	RCP8p5 HadGem noCO2	9%	HealthySustDiet	-12%	RCP8p5 IPSL	9%
LCR	RCP2p6 NOR	-46%	RCP8p5 HadGem noCO2	33%	HealthySustDiet	-30%	RCP8p5 IPSL	33%
MNA	RCP2p6 NOR	-54%	TradeOpen	12%	HealthySustDiet	-17%	RCP2p6 MIROC	12%
SAR	RCP8p5 HadGem noCO2	-13%	TradeRestr	4%	RCP8p5 HadGem noCO2	-12%	RCP2p6 NOR	4%
WLD	RCP2p6 NOR	-15%	TradeOpen	7%	HealthySustDiet	-8%	RCP2p6 MIROC	7%

Table-9 Percent difference in cumulative irrigation investment costs from 2010-2050 from Invest scenario for each sensitivity scenario by region

AFR		**EAP**		**ECA**		**LCR**		**MNA**		**SAR**		**WLD**	
% difference from *Invest*		**% difference from *Invest***		**% difference from *Invest***		**% difference from *Invest***		**% difference from *Invest***		**% difference from *Invest***		**% difference from *Invest***	
WatrEff High	10	CombinedHigh2	27	CombinedHigh2	77	CombinedHigh2	24	WatrEff High	25	CombinedHigh	18	CombinedHigh2	24
TradeRestr	5	CombinedHigh	20	CombinedHigh	62	CombinedHigh	18	CombinedHigh	24	CombinedHigh2	15	CombinedHigh	22
RCP8p5 HadGem noCO2	3	RCP8p5 IPSL	13	RCP8p5 IPSL	39	WatrEff High	13	CombinedHigh2	18	RCP2p6 MIROC	10	RCP8p5 IPSL	13
CombinedHigh	1	WatrEff High	11	RCP8p5 HadGem noCO2	37	RCP2p6 MIROC	6	CombinedLow	14	WatrEff High	10	WatrEff High	12
Invest SSP3	-2	RCP8p5 HadGem noCO2	9	CombinedLow2	35	TradeOpen	6	CombinedLow2	14	RCP8p5 GFDL	5	RCP8p5 GFDL	9
RCP2p6 GFDL	-3	RCP2p6 MIROC	7	CombinedLow	35	RCP8p5 MIROC	4	RCP2p6 IPSL	4	RCP8p5 MIROC	5	RCP8p5 MIROC	8
TradeOpen	-3	RCP8p5 MIROC	6	RCP8p5 MIROC	35	Invest SSP3	0	RCP8p5 MIROC	2	TradeRestr	4	RCP2p6 MIROC	7
RCP8p5 IPSL	-4	TradeOpen	3	RCP8p5 GFDL	34	RCP8p5 NOR	0	TradeOpen	1	RCP8p5 NOR	4	RCP2p6 GFDL	5
RCP8p5 NOR	-6	RCP2p6 GFDL	1	RCP2p6 IPSL	27	TradeRestr	0	TradeRestr	0	Invest SSP3	2	RCP8p5 HadGem noCO2	5
WatrEff Low	-6	RCP8p5 GFDL	1	RCP2p6 GFDL	26	RCP2p6 GFDL	-2	RCP8p5 HadGEM	0	RCP8p5 IPSL	-1	RCP2p6 IPSL	4
RCP8p5 GFDL	-6	RCP8p5 NOR	-1	WatrEff High	23	RCP2p6 IPSL	-3	Invest SSP1	-1	TradeOpen	-1	TradeOpen	3
RCP2p6 MIROC	-6	CombinedLow2	-1	TradeOpen	20	RCP2p6 HadGEM	-4	RCP8p5 IPSL	-1	CombinedLow2	-2	CombinedLow	1
RCP8p5 MIROC	-8	CombinedLow	-1	RCP8p5 HadGEM	20	RCP8p5 IPSL	-4	RCP8p5 GFDL	-2	CombinedLow	-2	CombinedLow2	1
CombinedHigh2	-9	RCP2p6 IPSL	-1	RCP2p6 MIROC	16	RCP8p5 HadGem noCO2	-5	RCP2p6 GFDL	-2	RCP2p6 NOR	-2	RCP8p5 NOR	1
RCP8p5 HadGEM	-9	Invest SSP3	-1	RCP8p5 NOR	12	RCP8p5 HadGEM	-5	RCP2p6 MIROC	-2	RCP2p6 IPSL	-3	TradeRestr	0
RCP2p6 IPSL	-9	TradeRestr	-2	RCP2p6 HadGEM	3	RCP8p5 GFDL	-9	RCP2p6 HadGEM	-3	RCP2p6 GFDL	-5	RCP8p5 HadGEM	-1
HealthyDiet	-10	RCP8p5 HadGEM	-3	TradeRestr	-8	WatrEff Low	-12	Invest SSP3	-5	HealthySustDiet	-6	Invest SSP3	-3
RCP2p6 HadGEM	-15	RCP2p6 HadGEM	-4	WatrEff Low	-14	HealthyDiet	-16	HealthyDiet	-5	WatrEff Low	-8	RCP2p6 HadGEM	-5
HealthySustDiet	-17	HealthyDiet	-5	Invest SSP3	-20	CombinedLow	-19	HealthySustDiet	-6	HealthyDiet	-9	WatrEff Low	-8
Invest SSP1	-19	WatrEff Low	-7	HealthyDiet	-20	CombinedLow2	-19	RCP8p5 HadGem noCO2	-10	RCP2p6 HadGEM	-11	HealthyDiet	-9
CombinedLow	-23	HealthySustDiet	-7	HealthySustDiet	-23	HealthySustDiet	-21	WatrEff Low	-18	RCP8p5 HadGEM	-12	HealthySustDiet	-12
CombinedLow2	-23	Invest SSP1	-9	Invest SSP1	-23	Invest SSP1	-32	RCP8p5 NOR	-23	Invest SSP1	-13	Invest SSP1	-15
RCP2p6 NOR	-51	RCP2p6 NOR	-18	RCP2p6 NOR	-40	RCP2p6 NOR	-49	RCP2p6 NOR	-30	RCP8p5 HadGem noCO2	-19	RCP2p6 NOR	-27

Table10. Percent difference in cumulative irrigation investment costs from 2010-2050 from *MaxInvest* scenario for each sensitivity scenario by region

AFR		**EAP**		**ECA**		**LCR**		**MNA**		**SAR**		**WLD**	
% difference from *Invest*		**% difference from *Invest***		**% difference from *Invest***		**% difference from *Invest***		**% difference from *Invest***		**% difference from *Invest***		**% difference from *Invest***	
CombinedHigh	14	CombinedHigh2	19	CombinedHigh2	130	CombinedHigh2	31	CombinedHigh	22	CombinedHigh	22	CombinedHigh	27
WatrEff High	10	RCP8p5 IPSL	17	CombinedHigh	113	CombinedHigh	28	WatrEff High	19	CombinedHigh2	16	CombinedHigh2	27
Invest SSP3	8	CombinedHigh	17	TradeOpen	72	WatrEff High	19	CombinedHigh2	16	RCP2p6 MIROC	10	RCP8p5 IPSL	18
TradeRestr	6	RCP8p5 HadGem noCO2	16	CombinedLow	62	RCP2p6 MIROC	17	CombinedLow	12	WatrEff High	9	RCP2p6 MIROC	13
CombinedHigh2	5	WatrEff High	12	CombinedLow2	62	RCP8p5 MIROC	12	CombinedLow2	12	RCP2p6 NOR	9	WatrEff High	12
RCP8p5 MIROC	4	RCP2p6 MIROC	10	RCP8p5 GFDL	60	TradeOpen	0	TradeOpen	2	TradeRestr	2	RCP8p5 MIROC	11
RCP8p5 HadGem noCO2	3	RCP2p6 IPSL	8	RCP8p5 IPSL	60	Invest SSP3	0	RCP2p6 IPSL	2	RCP8p5 MIROC	1	RCP8p5 GFDL	11
RCP2p6 NOR	3	RCP2p6 GFDL	6	RCP8p5 MIROC	55	RCP8p5 IPSL	-1	HealthyDiet	-1	Invest SSP3	1	RCP2p6 GFDL	10
TradeOpen	1	RCP8p5 MIROC	6	RCP8p5 HadGem noCO2	50	RCP8p5 HadGem noCO2	-1	RCP2p6 HadGEM	-1	RCP2p6 GFDL	0	RCP2p6 IPSL	9
RCP2p6 GFDL	0	CombinedLow	5	RCP2p6 IPSL	47	RCP8p5 NOR	-2	TradeRestr	-2	RCP8p5 NOR	0	RCP8p5 HadGem noCO2	7
RCP2p6 MIROC	-1	CombinedLow2	5	RCP2p6 GFDL	44	RCP2p6 NOR	-3	RCP2p6 GFDL	-2	RCP8p5 GFDL	-1	CombinedLow	7
RCP8p5 NOR	-2	Invest SSP3	5	RCP2p6 MIROC	44	TradeRestr	-3	HealthySustDiet	-3	TradeOpen	-4	CombinedLow2	7
HealthyDiet	-4	RCP8p5 NOR	5	RCP8p5 HadGem	38	RCP8p5 HadGem	-7	Invest SSP3	-3	RCP2p6 IPSL	-6	TradeOpen	5
RCP2p6 HadGEM	-5	RCP8p5 HadGem	4	WatrEff High	32	RCP8p5 GFDL	-8	Invest SSP1	-4	HealthyDiet	-6	RCP2p6 NOR	4
RCP8p5 GFDL	-6	TradeOpen	4	RCP8p5 NOR	25	RCP2p6 GFDL	-9	RCP8p5 HadGem	-6	RCP8p5 IPSL	-7	RCP8p5 NOR	3
RCP8p5 HadGem	-6	TradeRestr	2	RCP2p6 NOR	20	RCP2p6 IPSL	-10	RCP8p5 HadGem noCO2	-8	HealthySustDiet	-8	Invest SSP3	2
RCP8p5 IPSL	-8	RCP2p6 HadGEM	0	RCP2p6 HadGEM	14	RCP2p6 HadGEM	-14	RCP2p6 MIROC	-8	WatrEff Low	-8	RCP8p5 HadGem	1
RCP2p6 IPSL	-10	RCP2p6 NOR	-2	TradeRestr	-13	WatrEff Low	-17	RCP8p5 MIROC	-8	CombinedLow	-10	TradeRestr	0
WatrEff Low	-10	RCP8p5 GFDL	-3	WatrEff Low	-22	CombinedLow	-19	RCP8p5 IPSL	-10	CombinedLow2	-10	RCP2p6 HadGEM	-1
HealthySustDiet	-16	HealthyDiet	-8	Invest SSP3	-24	CombinedLow2	-19	RCP8p5 GFDL	-13	Invest SSP1	-12	HealthyDiet	-8
CombinedLow	-23	HealthySustDiet	-10	HealthyDiet	-26	HealthyDiet	-21	WatrEff Low	-18	RCP2p6 HadGEM	-12	HealthySustDiet	-11
CombinedLow2	-23	WatrEff Low	-15	Invest SSP1	-28	HealthySustDiet	-27	RCP8p5 NOR	-24	RCP8p5 HadGem	-17	WatrEff Low	-12
Invest SSP1	-23	Invest SSP1	-15	HealthySustDiet	-30	Invest SSP1	-30	RCP2p6 NOR	-26	RCP8p5 HadGem noCO2	-18	Invest SSP1	-14

Table 11 Irrigation infrastructure investment costs as a percent of the regional GDP discounted at 6% (%)

Scenario	**Year**	AFR	EAP	ECA	LCR	MNA	SAR	WLD
Invest	2020	0.43	0.19	0.05	0.10	0.13	0.37	0.07
	2030	0.36	0.13	0.04	0.08	0.11	0.27	0.06
	2040	0.31	0.11	0.04	0.07	0.09	0.22	0.06
	2050	0.27	0.10	0.04	0.07	0.08	0.19	0.05
MaxInvest	2020	0.72	0.29	0.18	0.19	0.16	0.53	0.11
	2030	0.68	0.20	0.17	0.19	0.14	0.37	0.10
	2040	0.65	0.17	0.15	0.19	0.12	0.29	0.09
	2050	0.58	0.15	0.14	0.18	0.10	0.25	0.09

Table 12 Cumulative irrigation infrastructure investment costs as a percent of the cumulative regional GDP from 2010-2030 and 2030-2050, calculated as an average of the ratio of costs to GDP undiscounted (%)

Scenario	Year	AFR	EAP	ECA	LCR	MNA	SAR	WLD
Invest	2010-2030	0.36	0.13	0.04	0.08	0.10	0.27	0.06
	2030-2050	0.16	0.05	0.03	0.04	0.04	0.08	0.03
MaxInvest	2010-2030	0.68	0.20	0.17	0.19	0.13	0.37	0.10
	2030-2050	0.45	0.07	0.09	0.16	0.05	0.10	0.06

6. Conclusion

Achieving ambitious expansion of irrigation and increase in irrigated cropland productivity in developing countries where large-scale and on-farm capital costs are heavily subsidized would cost $50 billion per year over the next 40 years and bring 154 million hectares of irrigated area into production by 2050. The construction of new irrigation infrastructure (i.e. providing access to water for irrigation and equipping rainfed cropland with irrigation equipment) would cost $16 billion per year, $32.7 billion per year would be needed for depreciation costs, $0.6 billion for upgrading irrigation systems to more efficient systems (i.e. moving from gravity-based irrigation systems to sprinkler or drip), and $0.2 billion for general efficiency improvements of irrigation systems (i.e. improving the water application efficiency of gravity-based irrigation systems).

Benefits from such large investments are not distributed equally across regions or development goals. Irrigating 73% of the FAO defined potentially irrigable area would lead to improvement in food availability and hence contribute to improved food security in all the considered regions (SDG2). However, the effectiveness and efficiency in achieving this goal through expanded irrigation differs substantially across regions; an investment of $4.3 billion per year would improve the food availability in Sub-Saharan Africa by less than 1% by 2050 while an investment of $6.8 billion per year would improve the food availability in South Asia by 2.5% by 2050.

Expanding irrigated areas by 70% in developing countries would lead to significant impacts in the environmental flows and the biodiversity in inland waters (SDG6). Ambitious irrigation support could lead to an increase in the share of surface water withdrawals for irrigation at risk to become unsustainable. Most notably, in South Asia and the Middle East and North Africa the share of surface water withdrawals at risk to become unsustainable could reach 51% and 66% by 2050 respectively. Historically in many regions, increases in production have come from the expansion of cropland area rather than through intensification or yield improvements (Byerlee et al., 2014; Fischer et al., 2014; Hillocks, 2002). Irrigation investments could save about 5 Mha of cropland from being converted and 10.1 Mha of other natural land, however forest area could decrease by 6.5 Mha (SDG15).

Irrigation can be used to help regions to adapt to the food security challenges from climate change (SDG2 and SDG13). By 2050, the impacts from climate change will reduce global calorie availability especially in South Asia where calorie availability will drop by 4% compared to baseline in 2050. Investments in irrigation can help increase calorie availability in nearly all developing regions (by 80 kcal/cap/day in South Asia and 30 kcal/cap/day globally under the most ambitious investment). Achieving this level of food security will cost less annually under climate change by $495 million under moderate investment and $1.7 billion under ambitious investment.

Our scenario analysis was complemented by a comprehensive uncertainty assessment which examined the role of macroeconomic development, climate change, future diets, water efficiency and trade policies. We observed that climate change scenarios and trade policies are the most likely to affect irrigation strategies and their impacts across the SDGs.

We find that multiple benefits would accrue from large-scale irrigation investments, in terms of efficiency of irrigation systems, food availability, and land sparing and our multi-criteria analysis finds that the most relevant regions for investment would be Europe and Central Asia, Middle East and North Africa, and South Asia where substantial benefits are to be expected with limited negative effects.

References

Adamson, D., Loch, A., 2014. Possible negative feedbacks from "gold-plating" irrigation infrastructure. Agric. Water Manag. 145, 134–144. doi:10.1016/j.agwat.2013.09.022

Alexandratos, N., Bruinsma, J., 2012. The 2012 Revision World agriculture towards 2030/2050: the 2012 revision (No. 12-03). Rome.

Arthington, A.H., Bunn, S.E., Poff, L.N., Naiman, R.J., 2006. The challenge of providing environmental flow rules to sustian river ecosystems. Ecol. Appl. 16, 1311–1318. doi:10.1890/1051-0761%25282006%2529016%255B1311%253ATCOPEF%255D2.0.CO%253B2

Baldos, U.L.C., Hertel, T.W., 2015. The role of international trade in managing food security risks from climate change. Food Secur. 7, 275–290. doi:10.1007/s12571-015-0435-z

Balkovič, J., van der Velde, M., Schmid, E., Skalský, R., Khabarov, N., Obersteiner, M., Stürmer, B., Xiong, W., 2013. Pan-European crop modelling with EPIC: Implementation, up-scaling and regional crop yield validation. Agric. Syst. 120, 61–75. doi:10.1016/j.agsy.2013.05.008

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., M.Reichstein, Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob. Chang. Biol. 13, 679–706. doi:10.1111/j.1365-2486.2006.01305.x

Bonsch, M., Humpen??der, F., Popp, A., Bodirsky, B., Dietrich, J.P., Rolinski, S., Biewald, A., Lotze-Campen, H., Weindl, I., Gerten, D., Stevanovic, M., 2016. Trade-offs between land and water requirements for large-scale bioenergy production. GCB Bioenergy 8, 11–24. doi:10.1111/gcbb.12226

Briscoe, J., 1999. The financing of hydropower, irrigation and water supply infrastructure in developing countries. Int. J. Water Resour. Dev. 15, 459–491. doi:10.1080/07900629948718

Byerlee, D., Stevenson, J., Villoria, N., 2014. Does intensification slow crop land expansion or encourage deforestation? Glob. Food Sec. 3, 92–98. doi:10.1016/j.gfs.2014.04.001

Cosgrove, W.J., Rijsberman, F.R., 2000. World Water Vision: Making Water Everybody's Business. Earthscan Publications Ltd, London.

Crespo Cuaresma, J., 2015. Income projections for climate change research: A framework based on human capital dynamics. Glob. Environ. Chang. IN PRESS. doi:10.1016/j.gloenvcha.2015.02.012

de Fraiture, C., Wichelns, D., 2010. Satisfying future water demands for agriculture. Agric. Water Manag. 97, 502–511. doi:10.1016/j.agwat.2009.08.008

Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the Shared Socioeconomic Pathways. Glob. Environ. Chang. 42, 200–214. doi:10.1016/j.gloenvcha.2015.06.004

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B.M., Folberth, C., Foster, I., Gosling, S.N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A.C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., Wisser, D., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proc. Natl. Acad. Sci. U. S. A. 111, 3239–44. doi:10.1073/pnas.1222474110

English, M., Raja, S., 1996. Perspectives on deficit irrigation. Agric. Water Manag. 32, 1–14. doi:10.1016/S0378-3774(96)01255-3

Evans, R.G., Sadler, E.J., 2008. Methods and technologies to improve efficiency of water use. Water Resour. Res. 44, 1–15. doi:10.1029/2007WR006200

FAO, F. and A.O., 2017. AQUASTAT Main database [WWW Document]. URL http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en (accessed 12.31.17).

FAO, F. and A.O., 2008. Water and the rural poor interventions for improving livelihoods in sub-Saharan Africa. FAO.

Fischer, T., Byerlee, D., Edmeades, G., 2014. Crop yields and global food security: Will yield increase continue to feed the world? ACIAR Monogr. 634. doi:978 1 925133 06 6

Foster, V., Briceno-Garmendia, C., 2009. Africa's Infrastructure. The World Bank. doi:10.1596/978-0-8213-8041-3

Frenken, K. (Ed. ., 2013. Irrigation in Central Asia in figures: Aquastat Survey - 2012 FAO Water Reports, 39th ed. ood and Agriculture Organization of the United Nations (FAO, Rome.

Frenken, K. (Ed. ., 2011. Irrigation in Southern and Eastern Asia in figures: Aquastat Survey - 2011 FAO Water Reports, 37th ed. Food and Agriculture Organization of the United Nations (FAO, Rome.

Frenken, K. (Ed. ., 2009. Irrigation in the Middle East region in figures: Aquastat Survey - 2008 FAO Water Reports, 34th ed. Food and Agriculture Organization of the United Nations (FAO), Rome.

Frenken, K. (Ed. ., 2005. Irrigation in Africa in figures: AQUASTAT Survey - 2005 FAO Water Reports, 29th ed. Food Agriculture Organization of the United Nations (FAO), Rome.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D.L., Obersteiner, M., Pachauri, S., Rao, S., Schmid, E., Schoepp, W., Riahi, K., 2017. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Glob. Environ. Chang. 42, 251–267. doi:10.1016/j.gloenvcha.2016.06.004

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., Sitch, S., 2004. Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model. J. Hydrol. 286, 249–270. doi:10.1016/J.JHYDROL.2003.09.029

Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D., Allen, R.G., 2018. The paradox of irrigation efficiency. Science (80-.). 361, 748–750. doi:10.1126/science.aat9314

Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., Kainuma, M., Kanamori, Y., Masui, T., Takahashi, K., Kanae, S., 2013. A global water scarcity assessment under Shared Socio-economic Pathways - Part 1: Water use. Hydrol. Earth Syst. Sci. 17, 2375–2391. doi:10.5194/hess-17-2375-2013

Havlík, P., Schneider, U. a., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., Cara, S. De, Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., Obersteiner, M., 2011a. Global land-use implications of first and second generation biofuel targets. Energy Policy 39, 5690–5702. doi:10.1016/j.enpol.2010.03.030

Havlík, P., Schneider, U. a., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., Cara, S. De, Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., Obersteiner, M., 2011b. Global land-use implications of first and second generation biofuel targets. Energy Policy 39, 5690–5702. doi:10.1016/j.enpol.2010.03.030

Havlik, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M.C., Mosnier, A., Thornton, P.K., Bottcher, H., Conant, R.T., Frank, S., Fritz, S., Fuss, S., Kraxner, F., Notenbaert, A., 2014. Climate change mitigation through livestock system transitions. Proc. Natl. Acad. Sci. 111, 3709–3714. doi:10.1073/pnas.1308044111

Herrero, M., Havlik, P., McIntire, J.M., Palazzo, A., Valin, H., 2014. African Livestock Futures: Realizing the Potential of Livestock for Food Security, Poverty Reduction and the Environment in Sub-Saharan Africa. Geneva, Switzerland.

Hillocks, R.J., 2002. Cassava in Africa., in: Cassava: Biology, Production and Utilization. CABI, Wallingford, pp. 41–54. doi:10.1079/9780851995243.0041

Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E., Richter, B.D., 2012. Global monthly water scarcity: Blue water footprints versus blue water availability. PLoS One 7. doi:10.1371/journal.pone.0032688

Inocencio, A., Kikuchi, M., Merrey, D.J., Tonosaki, M., Maruyama, A., Jong, I. de, Sally, H., Penning de Vries, F.W.T., 2005. Lessons from irrigation investment experiences: cost-reducing and performance-enhancing options for Sub-Saharan Africa. International Water Management Institute (IWMI).

Jiang, L., O'Neill, B.C., 2015. Global urbanization projections for the Shared Socioeconomic Pathways. Glob. Environ. Chang. doi:10.1016/j.gloenvcha.2015.03.008

KC, S., Lutz, W., 2017. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Glob. Environ. Chang. 42, 181–192. doi:10.1016/j.gloenvcha.2014.06.004

Konzmann, M., Gerten, D., Heinke, J., 2013. Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model. Hydrol. Sci. J. 58, 88–105. doi:10.1080/02626667.2013.746495

Leclère, D., Havlík, P., Fuss, S., Schmid, E., Mosnier, A., Walsh, B., Valin, H., Herrero, M., Khabarov, N., Obersteiner, M., 2014a. Climate change induced transformations of agricultural systems: insights from a global model. Environ. Res. Lett. 9, 124018. doi:10.1088/1748-9326/9/12/124018

Leclère, D., Havlík, P., Fuss, S., Schmid, E., Mosnier, A., Walsh, B., Valin, H., Herrero, M., Khabarov, N., Obersteiner, M., 2014b. Climate change induced transformations of agricultural systems: insights from a global model. Environ. Res.

Lett. 9, 124018. doi:10.1088/1748-9326/9/12/124018

Leimbach, M., Kriegler, E., Roming, N., Schwanitz, J., 2015. Future growth patterns of world regions – A GDP scenario approach. Glob. Environ. Chang. doi:10.1016/j.gloenvcha.2015.02.005

Miao, Q., Shi, H., Gonçalves, J.M., Pereira, L.S., 2018. Basin irrigation design with multi-criteria analysis focusing on water saving and economic returns: Application to wheat in hetao, yellow river basin. Water (Switzerland) 10. doi:10.3390/w10010067

Molden, D. (Ed.), 2007. Water for Food, Water for Life, A Comprehensive Assessment of Water Management in Agriculture. International Water Management Institute ; Earthscan.

Mosnier, A., Obersteiner, M., Havlík, P., Schmid, E., Khabarov, N., Westphal, M., Valin, H., Frank, S., Albrecht, F., 2014. Global food markets, trade and the cost of climate change adaptation. Food Secur. 6, 29–44. doi:10.1007/s12571-013-0319-z

Müller, C., Cramer, W., Hare, W.L., Lotze-Campen, H., 2011. Climate change risks for African agriculture. Proc. Natl. Acad. Sci. U. S. A. 108, 4313–4315. doi:10.1073/pnas.1015078108

Nelson, G.C., Rosegrant, M., Koo, J., Robertson, R., Sulser, T., Zhu, T., Msangi, S., Ringler, C., Palazzo, A., Batka, M., Magalhaes, M., Lee, D., 2009. Climate change: Impact on agriculture and costs of adaptation, Food Policy. doi:10.2499/089629535

Nelson, G.C., Rosegrant, M.W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S., Zhu, T., 2010. Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options, Research reports IFPRI. International Food Policy Research Institute. doi:10.2499/9780896291867

Nelson, G.C., Valin, H., Sands, R.D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., Von Lampe, M., Lotze-Campen, H., Mason d'Croz, D., van Meijl, H., van der Mensbrugghe, D., Müller, C., Popp, A., Robertson, R., Robinson, S., Schmid, E., Schmitz, C., Tabeau, A., Willenbockel, D., 2014a. Climate change effects on agriculture: economic responses to biophysical shocks. Proc. Natl. Acad. Sci. U. S. A. 111, 3274–9. doi:10.1073/pnas.1222465110

Nelson, G.C., van der Mensbrugghe, D., Ahammad, H., Blanc, E., Calvin, K., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., von Lampe, M., Mason d'Croz, D., van Meijl, H., Müller, C., Reilly, J., Robertson, R., Sands, R.D., Schmitz, C., Tabeau, A., Takahashi, K., Valin, H., Willenbockel, D., 2014b. Agriculture and climate change in global scenarios: why don't the models agree. Agric. Econ. 45, 85–101. doi:10.1111/agec.12091

NEPAD, N.P. for A.D., 2003. Comprehensive Africa Agriculture Development Programme Process and scope of the Agriculture Programme. New Partnership for Africa's Development (NEPAD); United Nations' Food and Agriculture Organisation (FAO), Midrand, South Africa.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42, 169–180. doi:10.1016/j.gloenvcha.2015.01.004

Palazzo, A., Brozović, N., 2014. The role of groundwater trading in spatial water management. Agric. Water Manag. 145, 50–60. doi:10.1016/j.agwat.2014.03.004

Palazzo, A., Havlik, P., Leclere, D., van Dijk, M., Deppermann, A., 2017. Hotspots in land and water resource uses on the way toward achieving the Sustainable Development Goals, in: Impacts World Conference. Potsdam.

Palazzo, A., Willaarts, B., Magnuszewski, P., Burek, P., Kahil, T., Tang, T., Byers, E., Pachauri, S., Krisztin, T., Riahi, K., Krey, V., Wada, Y., Langan, S., Obersteiner, M., Havlik, P., 2018. Integrated solutions for water, energy, and land nexus management the Zambezi Basin : stakeholder engagement and modeling, in: 3rd Zambezi Basin Stakeholders' Forum: Water- Energy-Food-Ecosystems (WEFE) Nexus for Socio- Economic Benefits in the Zambezi River Basin. ZAMCOM, Lilongwe, Malawi.

Pastor, A., Palazzo, A., Havlik, P., Obersteinner, M., Kabat, P., Ludwig, F., 2016. The future of irrigated agriculture under environmental flow requirements restrictions, in: European Geosciences Union (EGU) General Assembly. Vienna, Austria.

Pastor, A. V., Ludwig, F., Biemans, H., Hoff, H., Kabat, P., 2014. Accounting for environmental flow requirements in global water assessments. Hydrol. Earth Syst. Sci. 18, 5041–5059. doi:10.5194/hess-18-5041-2014

Portmann, F.T., Siebert, S., Döll, P., 2010. MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. Global Biogeochem. Cycles 24, n/a-n/a. doi:10.1029/2008GB003435

Robinson, S., Mason-D'Croz, D., Islam, S., Sulser, T.B., Robertson, R., Zhu, T., Gueneau, A., Pitois, G., Rosegrant, M., Technology, E. and P., 2015. The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) Model Description for Version 3 (No. 1483), IFPRI Discussion Paper. Washington D.C.

Robinson, S., van Meijl, H., Willenbockel, D., Valin, H., Fujimori, S., Masui, T., Sands, R., Wise, M., Calvin, K., Havlik, P., Mason d'Croz, D., Tabeau, A., Kavallari, A., Schmitz, C., Dietrich, J.P., von Lampe, M., 2014. Comparing supply-side specifications in models of global agriculture and the food system. Agric. Econ. (United Kingdom) 45, 21–35. doi:10.1111/agec.12087

Rogers, P., Bhatia, R., Huber, A., 1998. Water as a Social and Economic Good: How to Put the Principle into Practice, in: TAC Background Paper No. 2. Global Water Partnership, p. 35.

Rosegrant, M.W.., Sulser, T.B.., Mason-D'Croz, Daniel; Cenacchi, N., Nin-Pratt, A., Dunston, S., Zhu, T., Ringler, C., Wiebe, K.D.., Robinson, Sherman; Willenbockel, D., Xie, H., Kwon, H.-Y., Johnson, T., Thomas, Timothy S.; Wimmer, F., Schaldach, R., Nelson, G.C.., Willaarts, B., 2017. Quantitative foresight modeling to inform the CGIAR research portfolio. Project Report for USAID 225.

Roudier, P., Sultan, B., Quirion, P., Berg, A., 2011. The impact of future climate change on West African crop yields: What does the recent literature say? Glob. Environ. Chang. 21, 1073–1083. doi:10.1016/j.gloenvcha.2011.04.007

Schmidhuber, J., Bruinsma, J., Boedeker, G., 2009. Capital requirements for agriculture in developing countries to 2050, in: Expert Meeting on How to Feed the World in 2050.

Schmitz, C., van Meijl, H., Kyle, P., Nelson, G.C., Fujimori, S., Gurgel, A., Havlik, P., Heyhoe, E., D'Croz, D.M., Popp, A., Sands, R., Tabeau, A., van der Mensbrugghe, D., von Lampe, M., Wise, M., Blanc, E., Hasegawa, T., Kavallari, A., Valin, H., 2014. Land-use change trajectories up to 2050: insights from a global agro-economic model comparison. Agric. Econ. 45, 69–84. doi:10.1111/agec.12090

Simson, R., Tang, V.T., 2013. Food Security in ECOWAS, in: Fanta, E., Shaw, T.M., Tang, V.T. (Eds.), Comparative Regionalisms for Development in the 21st Century: Insights from the Global South. Ashgate, pp. 159–177.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2011. An Overview of CMIP5 and the Experiment Design. Bull. Am. Meteorol. Soc. 93, 485–498. doi:10.1175/BAMS-D-11-00094.1

Toan, T.D., 2016. Water Pricing Policy and Subsidies to Irrigation : a Review. Environ. Process. 1, 1081–1098. doi:10.1007/s40710-016-0187-6

Turral, H., Svendsen, M., Faures, J.M., 2010. Investing in irrigation: Reviewing the past and looking to the future. Agric. Water Manag. 97, 551–560. doi:10.1016/j.agwat.2009.07.012

Valin, H., Sands, R.D., van der Mensbrugghe, D., Nelson, G.C., Ahammad, H., Blanc, E., Bodirsky, B., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Mason-D'Croz, D., Paltsev, S., Rolinski, S., Tabeau, A., van Meijl, H., von Lampe, M., Willenbockel, D., 2014. The future of food demand: understanding differences in global economic models. Agric. Econ. 45, 51–67. doi:10.1111/agec.12089

van Beek, L.P.H., Wada, Y., Bierkens, M.F.P., 2011. Global monthly water stress: 1. Water balance and water availability. Water Resour. Res. 47. doi:10.1029/2010WR009791

van Dijk, M., 2011. African Regional Integration: Implications for Food Security.

Van Koppen, B., Namara, R., Safilios-Rothschild, C., 2005. Reducing Poverty and Gender Issues and Synthesis of Sub-Saharan Africa Case Study Reports (No. 101).

von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason d'Croz, D., Nelson, G.C., Sands, R.D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D., van Meijl, H., 2014a. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. Agric. Econ. 45, 3–20. doi:10.1111/agec.12086

von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason d'Croz, D., Nelson, G.C., Sands, R.D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D., van Meijl, H., 2014b. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. Agric. Econ. 45, 3–20. doi:10.1111/agec.12086

Wada, Y., Bierkens, M.F.P., 2014. Sustainability of global water use: past reconstruction and future projections. Environ. Res. Lett. 9, 104003. doi:10.1088/1748-9326/9/10/104003

Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., Satoh, Y., Van Vliet, M.T.H., Yillia, P., Ringler, C., Burek, P., Wiberg, D., 2016. Modeling global water use for the 21st century: The Water Futures and Solutions (WFaS) initiative and its approaches. Geosci. Model Dev. 9, 175–222. doi:10.5194/gmd-9-175-2016

Wada, Y., van Beek, L.P.H., van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., Bierkens, M.F.P., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37, n/a-n/a. doi:10.1029/2010GL044571

Wada, Y., Van Beek, L.P.H., Viviroli, D., Drr, H.H., Weingartner, R., Bierkens, M.F.P., 2011. Global monthly water stress: 2. Water demand and severity of water stress. Water Resour. Res. 47. doi:10.1029/2010WR009792

Wada, Y., Wisser, D., Bierkens, M.F.P., 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth Syst. Dyn. 5, 15–40. doi:10.5194/esd-5-15-2014

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., Schewe, J., 2014. The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework. Proc. Natl. Acad. Sci. 111, 3228–3232. doi:10.1073/pnas.1312330110

Wichelns, D., 2010. Agricultural Water Pricing: United States, OECD: Sustainable Management of Water Resources in Agriculture.

Winpenny, J., 2003. Financing water for all: Report of the World Panel on Financing Water Infrastructure (the “Camdessus Report”), World Water Council, the 3rd World Water Forum and the Global Water Partnership.

You, L., Ringler, C., Wood-Sichra, U., Robertson, R., Wood, S., Zhu, T., Nelson, G., Guo, Z., Sun, Y., 2011. What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. Food Policy 36, 770–782. doi:10.1016/j.foodpol.2011.09.001

You, L.Z., 2008. Africa Infrastructure Country Diagnostic: Irrigation Investment Needs in Sub-Saharan Africa (No. 48213), Background Paper 9.