Supplementary information for

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1. GLOBIOM Modeling Framework

GLOBIOM is a partial equilibrium model representing land-use based activities: agriculture, forestry and bioenergy sectors. The model is built following a bottom-up setting based on detailed gridcell information, providing the biophysical and technical cost information. GLOBIOM dynamically models the use cropland, pasture/grassland, managed and unmanaged forest, and other natural vegetation based on the relative profitability given the productivity of each land–use sector (Havlík et al., 2011; Robinson et al., 2015, 2014; Schmitz et al., 2014). Future land use change is based on the relative profitability of a new land cover class given land rents and nonlinear conversion costs.

With regards to representing cropland, GLOBIOM captures production systems and land use in its base year (2000), using available historical data from SPAM (You & Wood, 2006) which provides the physical area for 17 of the 18 crops included in GLOBIOM under four crop management systems: subsistence farming, low input rainfed, high input rainfed, and high input irrigated. GLOBIOM contains detailed crop supply representation based on spatially explicit production functions calibrated for four management systems, incl. irrigation, by means of the biophysical process based model EPIC (Balkovič et al., 2013; Williams and Singh, 1995). Production is calibrated to match FAO statistics at the country level. Global water and nitrogen balances are calculated through the coupling with EPIC which allows for greenhouse gas (GHG) emissions accounting in the crop sector, as well as a direct quantification of the spatially explicit climate change impacts on crop yields and irrigation water requirements in irrigated system. GLOBIOM also applies a detailed representation of the livestock production sector which includes demand for grassland. GLOBIOM represents the forest sector with five categories of primary products (pulp logs, saw logs, biomass for energy, traditional fuel wood, and other industrial logs) which are consumed by industrial energy, cooking fuel demand, or processed and sold on the market as final products (wood pulp and sawnwood). Forest products are supplied from managed forests and short rotation plantations. Harvesting cost and mean annual increments are informed by the G4 M global forestry model which in turn calculates them based on thinning strategies and length of the rotation period (Kindermann et al., 2006).

Supply side activities are modeled at a high spatial resolution using a global grid of 212,707 grid cells which are based on the heterogeneity in land characteristics and thus vary in size between 5 x 5 arcminutes (10 km by 10 km square at the equator) and 30 x 30 arcminutes pixels (50 x 50 km at the equator.

GLOBIOM uses a double-log demand system to model consumer food demand, considering both a dynamic adjustment to demand based on income growth as well as a demand response based on prices (Valin et al., 2014). International trade representation is based on the spatial equilibrium modelling approach, where individual regions trade with each other based purely on cost competitiveness because goods are assumed to be homogenous. GLOBIOM considers bilateral trade policies and barriers as well as transportation costs, making the regional prices more responsive to regional effect (Mosnier et al., 2014). Market equilibrium is determined through mathematical optimization which allocates land and other resources to maximize the sum of consumer and producer surplus. As in other partial equilibrium models, prices are endogenous. The model is run recursively dynamic with a 10 year time step, along a going from 2000 to 2100.

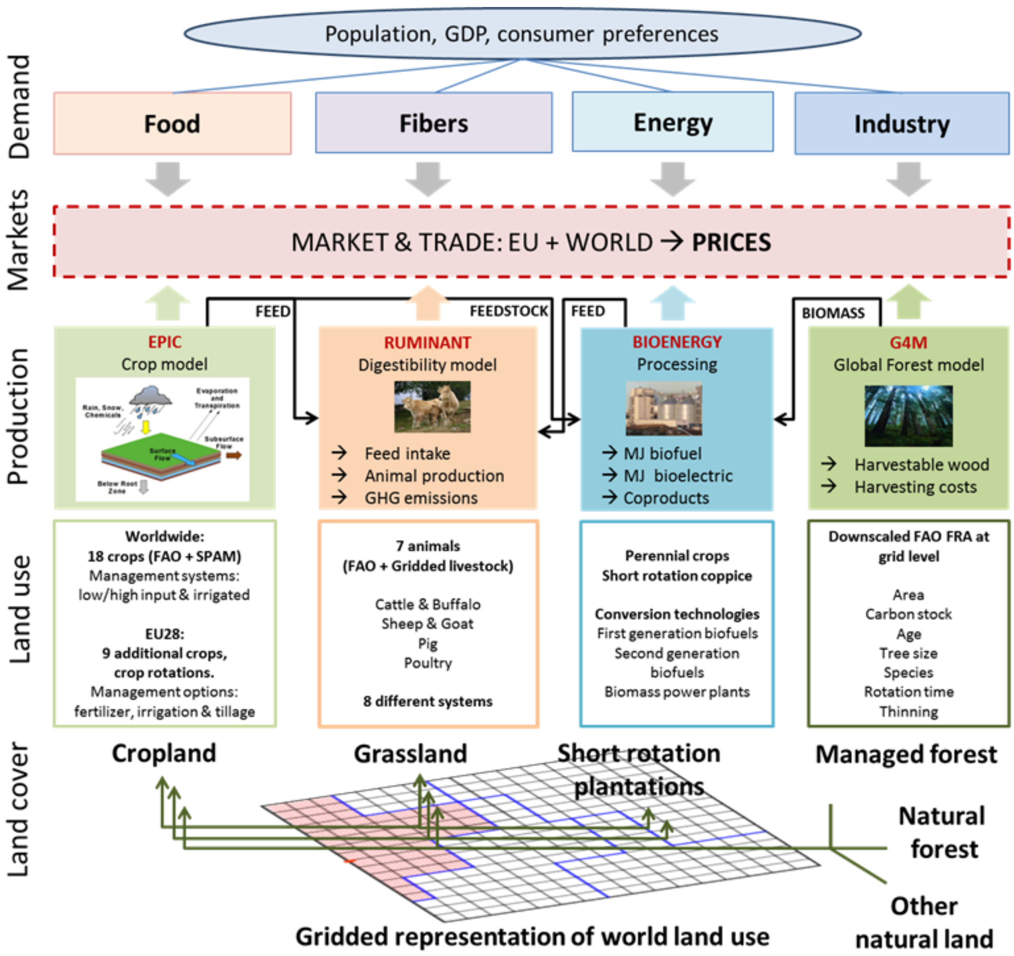

Figure SI 1. Illustrative representation of the bottom-up structure of GLOBIOM

1.1.Representation of irrigation

Crop production system

The representation of irrigated cropland production systems considers both the biophysical suitability and irrigation water requirements of crops at a monthly level which is simulated by EPIC and harmonized with the country-level FAO AQUASTAT statistics for water withdrawn for irrigation available from AQUASTAT (Palazzo et al., 2018). Four irrigation systems are modeled at a high spatial resolution for irrigated cropland – basin, furrow irrigation, localized drip, and sprinkler. Table B-1 briefly presents the biophysical and economic suitability and efficiency of each system that is taken into account in determining the crop/system compatibility for each land unit (Sauer et al., 2010). The shares of irrigated areas by systems Sauer et al. (2010) have been harmonized with shares of irrigated area by systems from Jaegermeyr et al. (2015). The final irrigation water demand for crops for a given land unit depends on the application efficiency of each system.

Table SI 1. Biophysical, technical, and economic factors considered for irrigation system/crop choice

Biophysical	Technical	Economic
Crop characteristics • water tolerance • rain-fed and irrigated yields • irrigation requirement • Length of growing period	Water application efficiency Operation time per irrigation event	Crop market prices Investment capital cost
Soil infiltration rate	level of pressurization (energy and labor requirement)	Energy prices
Slope inclination	Coverage per irrigation system unit	Labor cost
Water resource availability • Surface water • Groundwater • Non-renewable sources	Water application efficiency	Land and water prices

Representation of water availability and demand

GLOBIOM represents the spatial and temporal nature of water demand and supply by building on the work from Sauer et al. (2010) to consider the suitability of irrigation systems and crops by considering the biophysical conditions as well as the physical and economic suitability of crops for irrigation (Palazzo et al., 2018, 2017, Pastor et al., 2016, 2014). Water balance for irrigation was made spatially explicit for both the irrigation water demand and water supply availability, and considers now the source of water used for irrigation and seasonality of water and can reflect the impacts of socioeconomic change and climate change. Figure B-2 provides an overview of the conceptual framework representing the biophysical water availability and irrigation water demand within GLOBIOM.

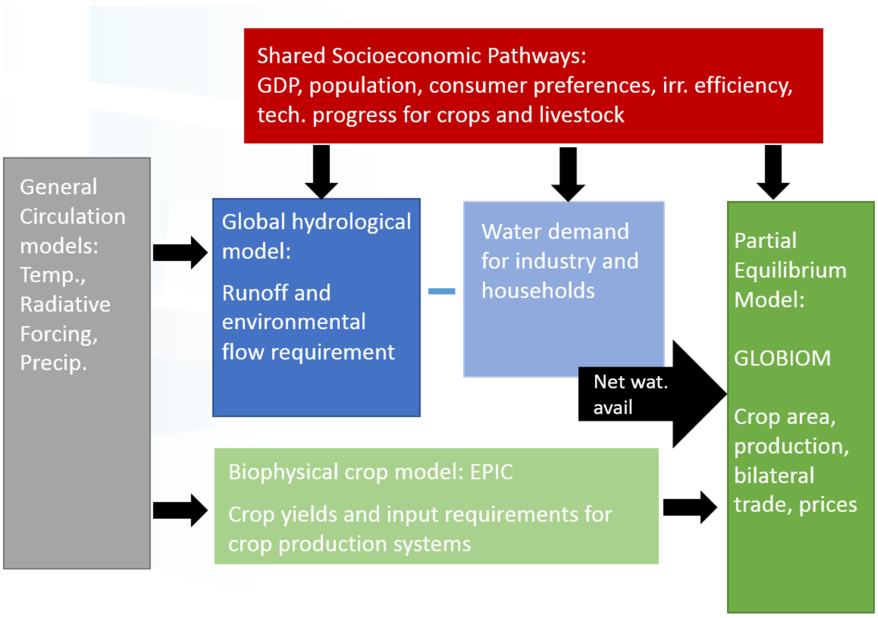

Figure SI 2. Conceptual framework for representing biophysical water availability and irrigation demand within a global land use model (adapted from Pastor et al., in review).

Irrigation water requirement by crop

Irrigation water requirements at the monthly level were calculated using the globally gridded crop model EPIC, which simulates the biophysical processes of crop growth under climatic, environmental and management conditions. These irrigation water requirements were harmonized for base year to match the water demands from Aquastat (FAO, 2016), using the irrigated cropland area dataset available from SPAM (You and Wood, 2006) to inform the irrigated area by crop.

1.2. Water supply by source

The source of water supplying irrigation is split into three categories: irrigation sourced by surface water, irrigation sourced by groundwater, and irrigation sourced by non-renewable sources. Return flows are an important consideration that we do not currently model within GLOBIOM. Stronger coupling between hydrological models and GLOBIOM in future analyses may allow for the feedbacks of return flows to be captured.

Surface water

Monthly surface water availability is simulated from 2000 to 2050 at a 0.5° x 0.5° spatial resolution using the LPJmL global hydrological model (Bondeau et al., 2007; Gerten et al., 2004). To use these data at the appropriate spatial resolution for GLOBIOM, the mean monthly runoff is estimated by aggregating according to the average discharge rates in each river basin. Additionally, runoff is estimated under the conditions of temperature, radiative forcing, and precipitation from different GCMs to consider the impact of climate change with respect to changes in water availability.

Groundwater and non-renewable water

We determine the share of irrigated area at 0.5° spatial resolution sourced by surface water and groundwater using a spatially explicit map of irrigated areas source from groundwater (Siebert et al., 2010). We estimated the total volume of water demanded by each source on a yearly basis using the shares and the total irrigation water requirement for all crop areas (see section "Irrigation water requirement by crop" above). The use of groundwater over the growing period is based on the share of irrigation water requirements that cannot be met by surface water due to limited monthly stream flows. If the available groundwater is in excess of the surface water deficit, the model distributes the excess groundwater supply according to the monthly demand for water. Non-renewable withdrawals were calculated as the water deficit that cannot be fulfilled by surface water or groundwater in year 2000. The amount of water withdrawal coming from groundwater and nonrenewable sources is assumed to remain constant over time. The method to determine the share of irrigation water withdrawals sourced by groundwater and surface water follows closely the methods outlined by Wada et al. (2014). These authors estimate that groundwater withdrawals account for 35% of the total irrigation withdrawals and 65% come from surface water or reservoirs.

1.3. Irrigation costs module

For the year 2000, the initial year of the simulation, the allocation of the three systems varies between regions and is based on the country level statistics available from Jaegermeyr et al. (2015). The three irrigation technologies are characterized by a corresponding water application efficiency (WAE), which also varies by region (Sauer et al., 2010). A resulting average water application efficiency is calculated for each region as a weighted average of the system WAEs in that region, weighted by the areas allocated into each system in that region.

For the simulation years from 2000 onward, average water application efficiency is based on exogenous assumptions. These assumptions rely on the quantification of water efficiency assumptions of the SSP scenarios from Hanasaki et al. (2013). The assumptions are translated into the GLOBIOM model as a 0.15% per year improvement in water application efficiency in the base scenarios, a 0.30% per year improvement in the high water efficiency scenarios, and a 0% improvement in the low water efficiency scenarios.

The investment module takes these exogenous assumptions as a target for the average water efficiency in the region and finds the combination of proportions of irrigated areas in each irrigation system which allows for the reaching of the given target average water application efficiency.

Application efficiency is lowest for surface systems and highest for drip systems. Improvement in the average WAE in a given region is therefore achieved by decreasing the proportion of the less efficient systems and increasing the share of the more efficient systems. As a matter of design, the investment module seeks to first reduce the proportion of the least efficient system in order to achieve the largest marginal increase in average WAE. As a result, the order of priority in the allocation is to replace the surface system with drip, followed by the replacement of the surface system with the sprinkler system, and as a last resort the replacement of sprinkler technology with drip technology.

In this process, the investment module is restricted by the suitability of different irrigation technologies for use on different crops. Specifically, it is assumed that rice is only suitable to be grown using a surface irrigation system. The proportion of rice in the total irrigated crop area in a given region is therefore taken as the minimum proportion of irrigated area which must be allocated into the surface system. In addition, it is assumed that a drip irrigation technology is only suitable for a certain number of other crops (beans, chickpea, cotton, groundnut, oil palm, soya, sugar cane, and sunflower). The proportion of irrigated area in a given region occupied by these crops is therefore the maximum proportion of irrigated area which can be allocated into the drip system.

Using the system allocations from the above procedure, the surface area in each system is calculated for each time period of the model. Changes in irrigated area from one period to the next are calculated and only positive changes from the previous time period (i.e. increases in irrigated area in a given system) are considered for the purposes of calculating investment needs. These positive changes in irrigated area by system represent increases which multiplied by per hectare unit costs yield the total costs of irrigation expansion and irrigation upgrades.

The unit costs are based on a review of “314 irrigation projects implemented from 1967 to 2003 in 50 countries in Sub-Saharan Africa, Asia, and Latin America funded (or assisted) by the World Bank, Sub-Saharan African Development Bank and the International Fund for Agriculture Development” (Inocencio et al., 2005). 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.

In the investment calculation, an increase in a given system area can potentially be considered to be either an expansion (new construction) or an upgrade (rehabilitation) of an existing, less efficient system. In a given region, if the area of a more efficient system (drip, sprinkler) increases while the area of a less efficient system (surface, sprinkler) decreases, then the increase of the more efficient system equal up to the decrease in the less efficient system is assumed to be an upgrade of a less efficient system, bearing the generally lower rehabilitation unit costs. If the increase in area of a more efficient system exceeds the decrease in area of a less efficient system, then this increase is considered an expansion of the new system bearing the costs of new construction.

Surface irrigation, being the least efficient system, can only increase through new construction. The unit costs of surface irrigation expansion are those of new irrigation construction taken directly from Inocencio et al. (2005). The upgrade from surface to either drip or a sprinkler system uses the unit costs of rehabilitation from the same source, while the upgrade from a sprinkler system to the drip system assumes 10% of the rehabilitation unit costs. The unit costs of drip or sprinkler system expansion are assumed to be the sum of the new construction and rehabilitation unit costs from Inocencio et al. (2005).

In situations where the composition of crops grown in a given region does not allow for any reallocation of irrigated area between irrigation technologies (i.e. no upgrades are possible either because of the restriction on the minimum share of the surface system or the restriction on the maximum share of the drip system), or in cases where exhausting even the maximum potential for system upgrades would not allow the region to reach the target WAE, the target WAE is achieved by evenly increasing the water application efficiencies of all three irrigation technologies. This increase represents a technological improvement in water efficiency in the distribution and delivery networks of these systems (as opposed to the efficiency of applying water to the crops on site) and it is assumed that this improvement would need to be applied to the entire existing irrigation system. The relative improvement in efficiencies required, multiplied by the unit costs of new construction, multiplied by the existing irrigated area, yields the total cost of irrigation efficiency improvement.

The final component of the irrigation investment calculations is the cost of depreciation and capital replacement, which must be borne in order to keep the existing and newly built irrigation infrastructure in good working order in the long run. The useful lifespan of irrigation schemes estimated to be approximately 40 years (FAO, 2003), we assume that annual depreciation and replacement costs equal 2.5% of the total existing capital stock. Given that GLOBIOM model operates on a 10-year time step, in each time period of the model simulation solution, the depreciation costs are 25% of the value of the capital stock which existed in the previous time period. The value of the capital stock of the entire existing irrigation system is calculated as the irrigated area multiplied by the unit costs of new construction as described above.

2. Supplemental results of the impacts of irrigation investments

In the following sections 2.1 to 2.5, we present additional results of the impacts of the investment scenarios for cropland area expansion, crop production, land use change and greenhouse gas emissions, and water withdrawals at World Bank regions level and the global level.

2.1. Expansion of cropland area

By 2050 under *ZeroInvest* and *Invest*, global cropland area expands by 181 Mha, while under *MaxInvest* cropland expands less (176 Mha) (Figure SI 3). In *ZeroInvest,* the lack of investment results in a decline in irrigated areas in developing countries by 2050 (Figure SI 2).

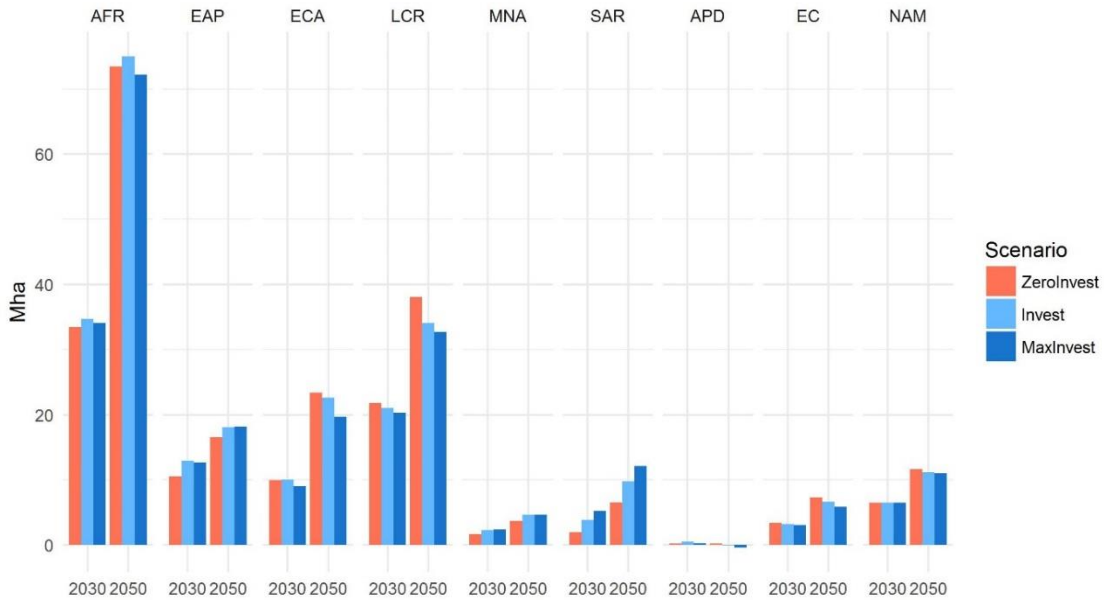

Figure SI 3. Total cropland area expansion in 2030 and 2050 compared to 2010 levels (Mha)

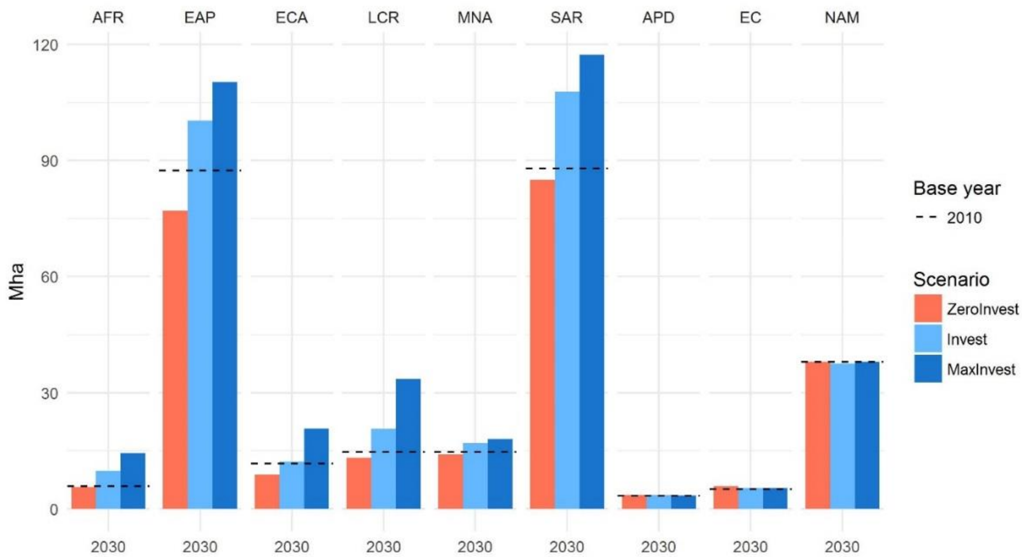

Figure SI 4. Irrigated area by region in 2010 and under *ZeroInvest*, *Invest*, and *MaxInvest* in 2030 (Mha)

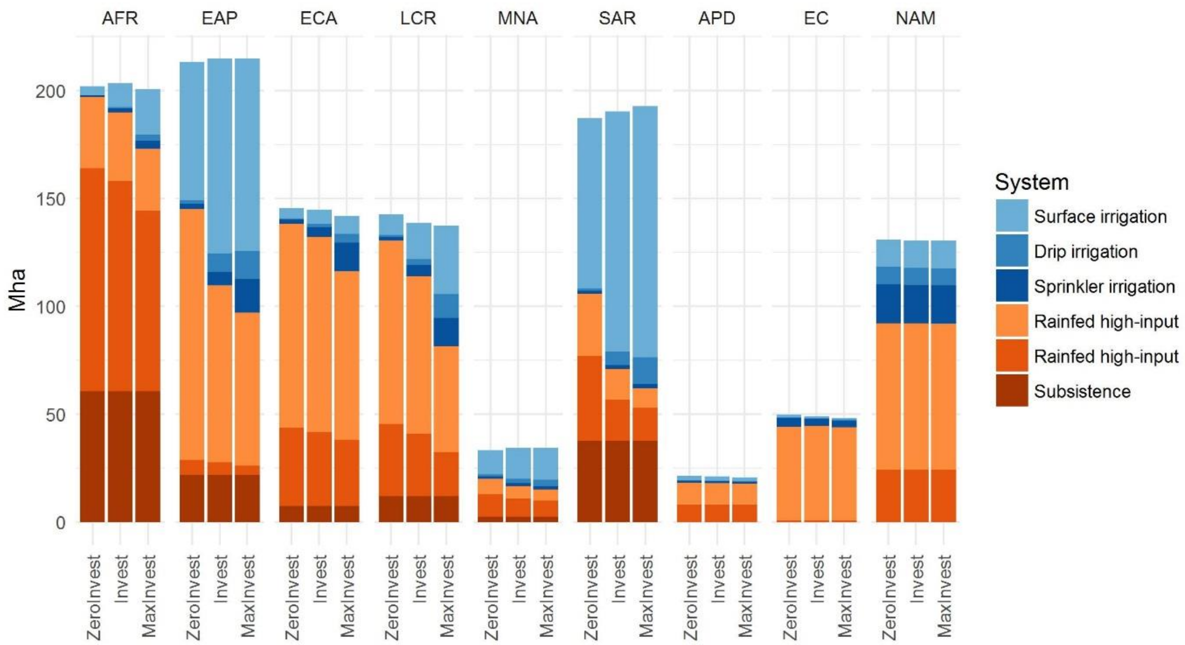

Figure SI 5. Irrigated area and rainfed area by system in 2050 by investment scenario (Mha)

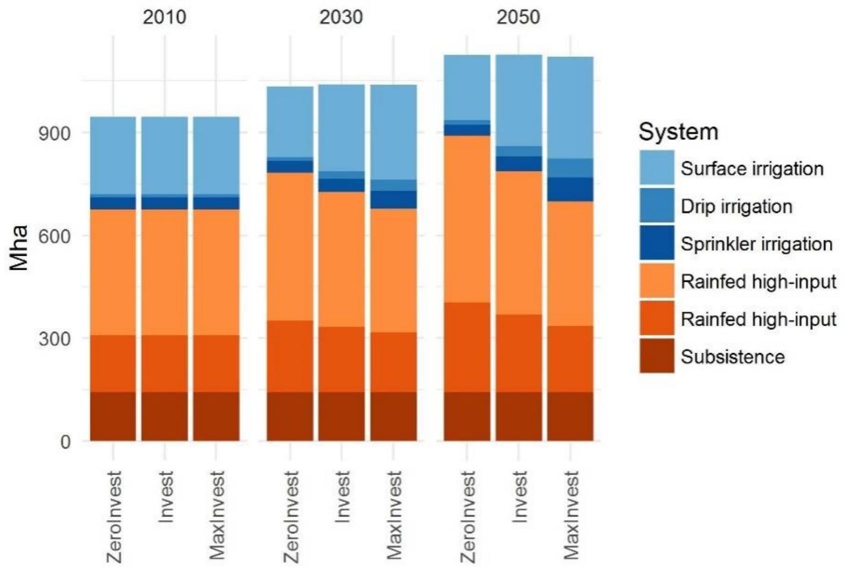

Figure SI 6. Cropland area by production system and investment scenario in 2010, 2030, and 2050 (Mha)

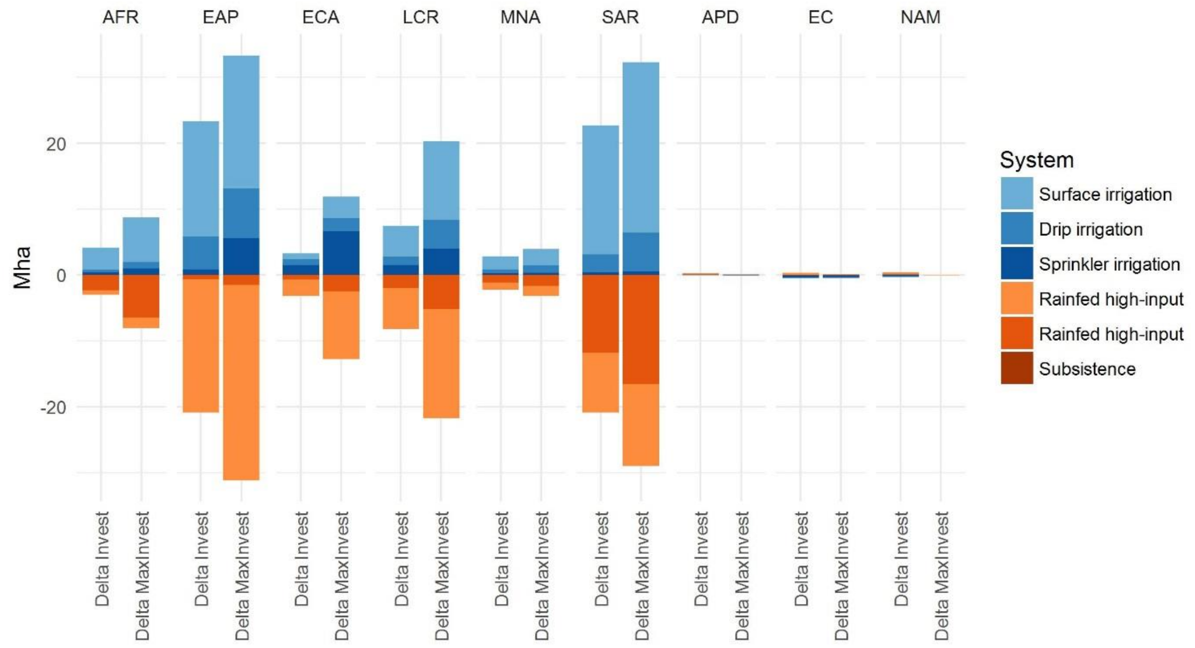

Figure SI 7. Difference in irrigated area and rainfed area by system compared to *ZeroInvest* in 2030 (Mha)

2.2.Crop production

In the following section we provide additional results and figures of crops that represent approx. 90% of irrigated areas.

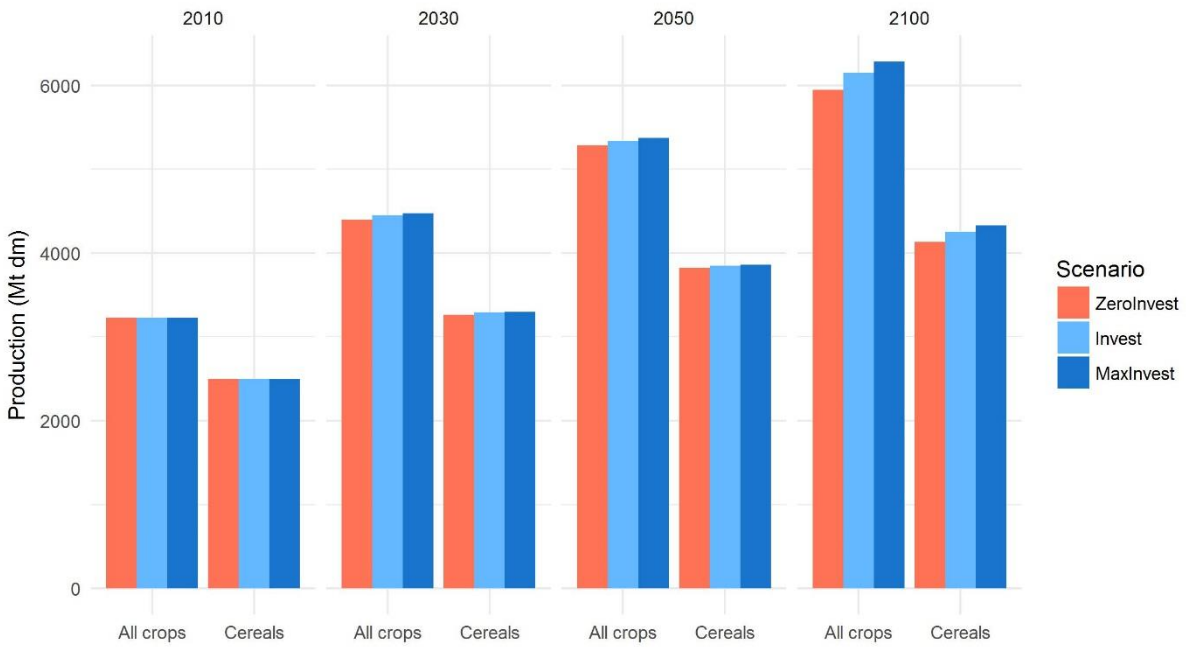

Figure SI 8. Global crop production for scenarios in 2010, 2030, 2050, 2100 (Mt dm)

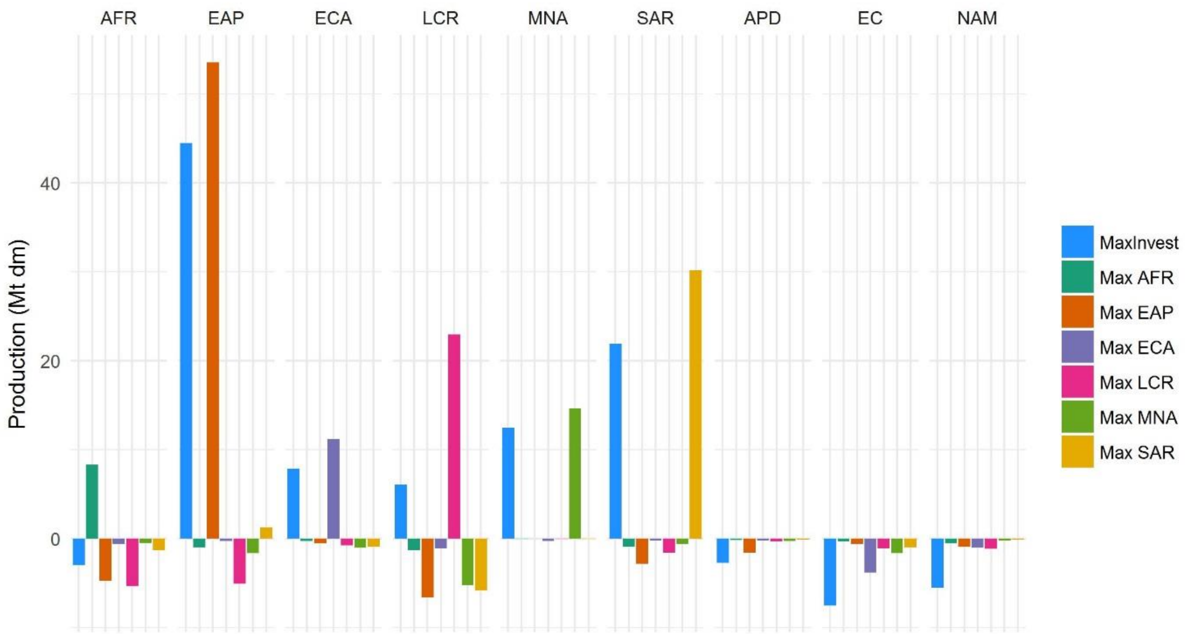

Figure SI 9. Difference in crop production under regional maximum investment scenarios compared to *ZeroInvest* in 2030 (Mt dm)

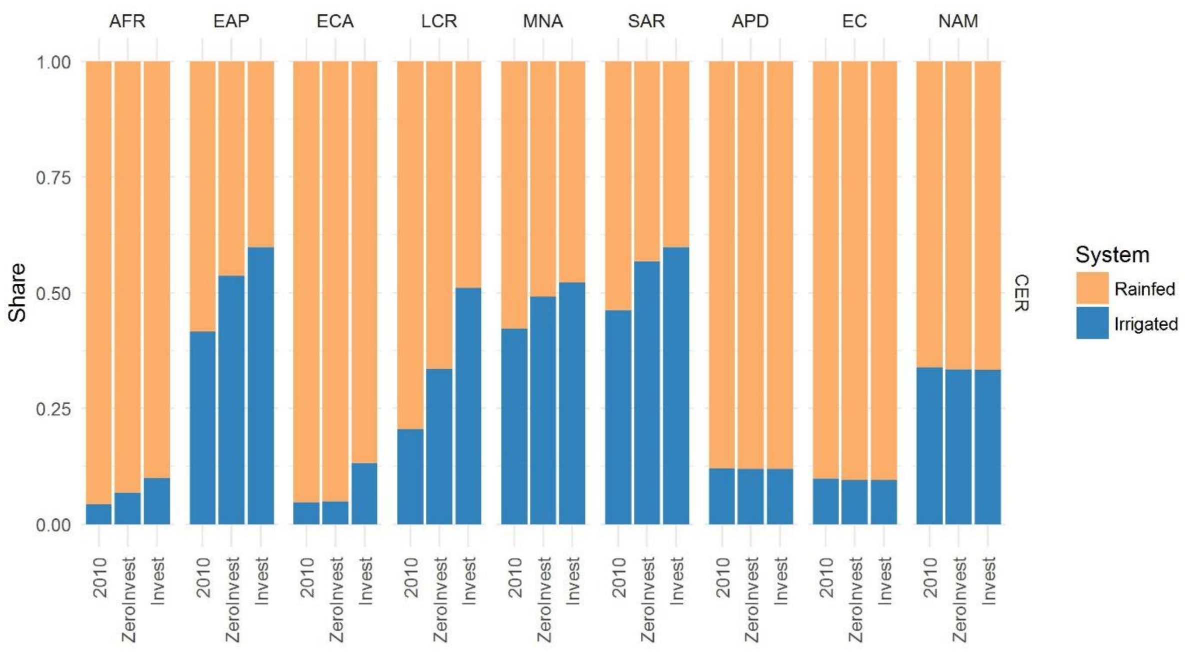

Figure SI 10. Share of cereal production that is irrigated in 2010 and 2030 in *Invest* and *ZeroInvest* by region (1.00 = 100%).

Corn

In 2010, more than half of the production was supplied by developing countries, and a little less than a quarter of corn of that supply in developing countries was produced using irrigation. Under *Invest*, in 2050 the irrigated share of supply in developing countries increases to 27% (34% in *MaxInvest*), but without investment the irrigated supply share drops to 15% of the total supply in developing countries (Figure SI 11).

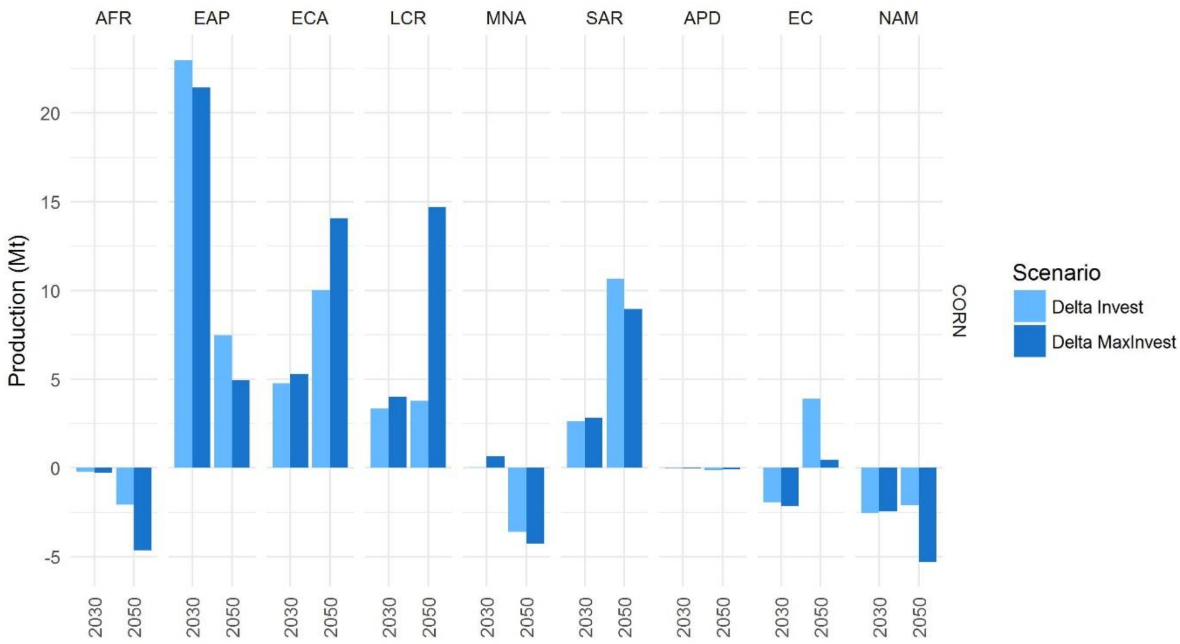

Figure SI 11. Difference in corn production relative to *ZeroInvest* in 2030 and 2050 (Mt)

Rice

In 2010, nearly the entire global supply of rice (97%) was produced in developing countries with about half of the total produced using irrigation. By 2050, under *Invest* the irrigated share of the supply from developing countries increases to 64% (74% in *MaxInvest*), but without investment the share drops to 42% of the total supply in developing countries (Figure SI 12).

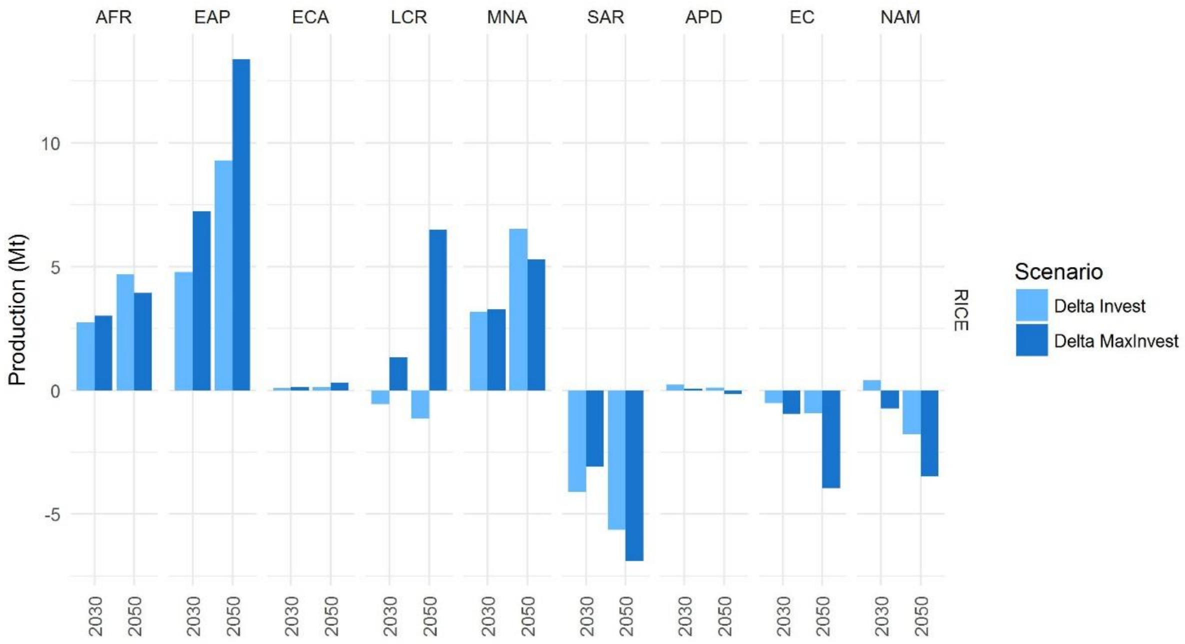

Figure SI 12. Difference in rice production relative to *ZeroInvest* in 2030 and 2050 (Mt)

Wheat

In 2010, two-thirds of the wheat supply was produced in developing countries, with only a quarter of wheat produced there using irrigation. By 2050, under *Invest* the irrigated share in developing countries increases to 30% (41% in *MaxInvest*), without investment the share drops to 23% of the total supply in developing countries (Figure SI 13).

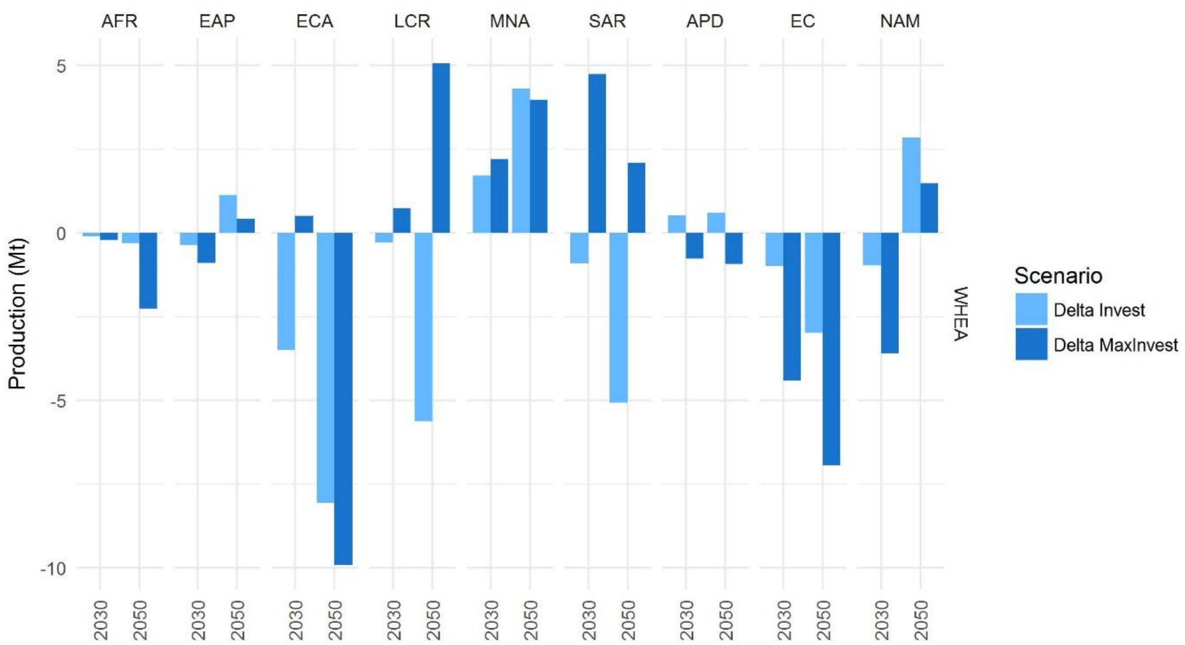

Figure SI 13. Difference in Wheat production relative to *ZeroInvest* in 2030 and 2050 (Mt)

Cotton

In 2010, nearly 85% of the cotton supply was produced in developing countries, with 64% produced using irrigation and without investment the share drops to 41% of the total supply in developing countries. By 2050, under *Invest* the supply from developing countries increases to 91% (92% in *MaxInvest*) of the total supply (Figure SI 14).

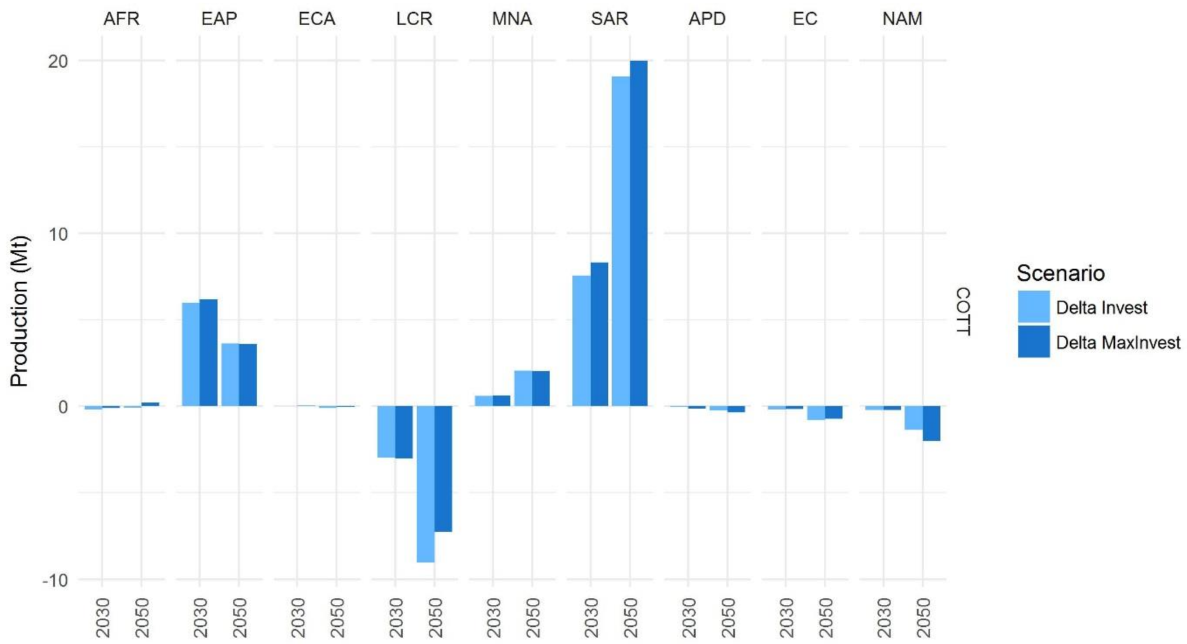

Figure SI 14. Difference in cotton production relative to *ZeroInvest* in 2030 and 2050 (Mt)

Sugar cane

In 2010, nearly all of the sugar cane supply was produced in developing countries, with 47% produced using irrigation. Without investment, by 2050, the share drops to 30% of the total supply in developing countries. By 2050, under *Invest* the irrigated supply from developing countries accounts for almost 40% (90% in *MaxInvest*) of the total supply (Figure SI 15).

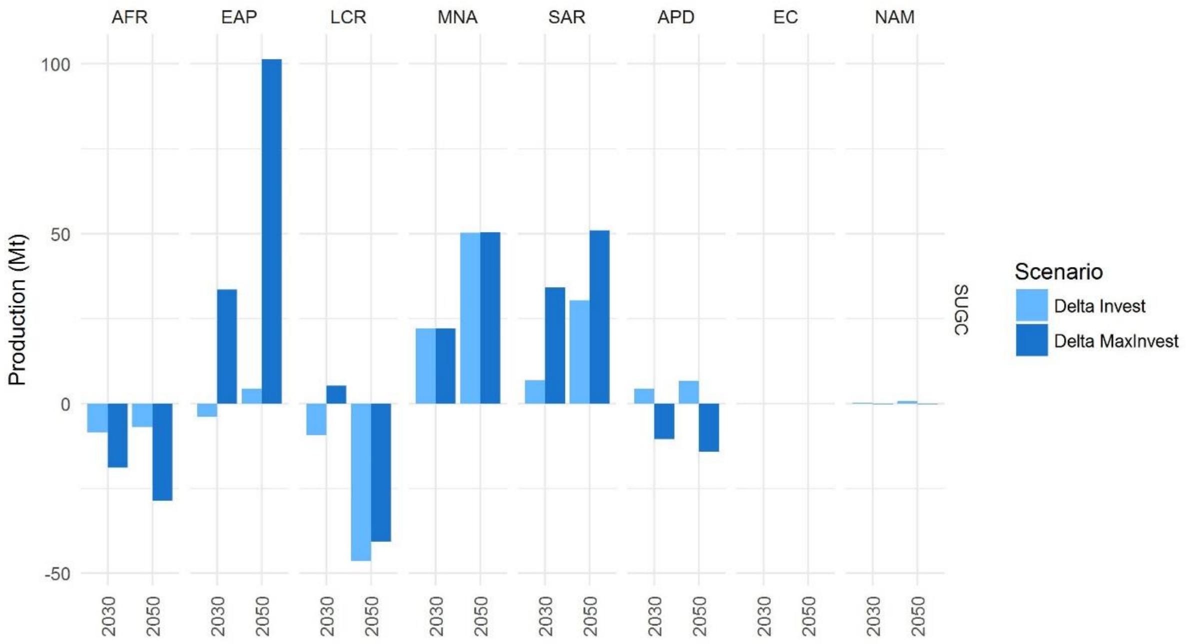

Figure SI 15. Difference in sugarcane production relative to *ZeroInvest* in 2030 and 2050 (Mt)

Soybean

In 2010, 56% of the soybean supply was produced in developing countries, with only 5% of soy produced using irrigation. By 2050, under *Invest* the share supplied by developing country increases to 68% and the share of irrigated production in developing countries increases to 6% of the total supply (14% in *MaxInvest*). The total global irrigated share of soy production in 2050 reaches 25% of the total soy production in *MaxInvest* by 2050 (Figure SI 16).

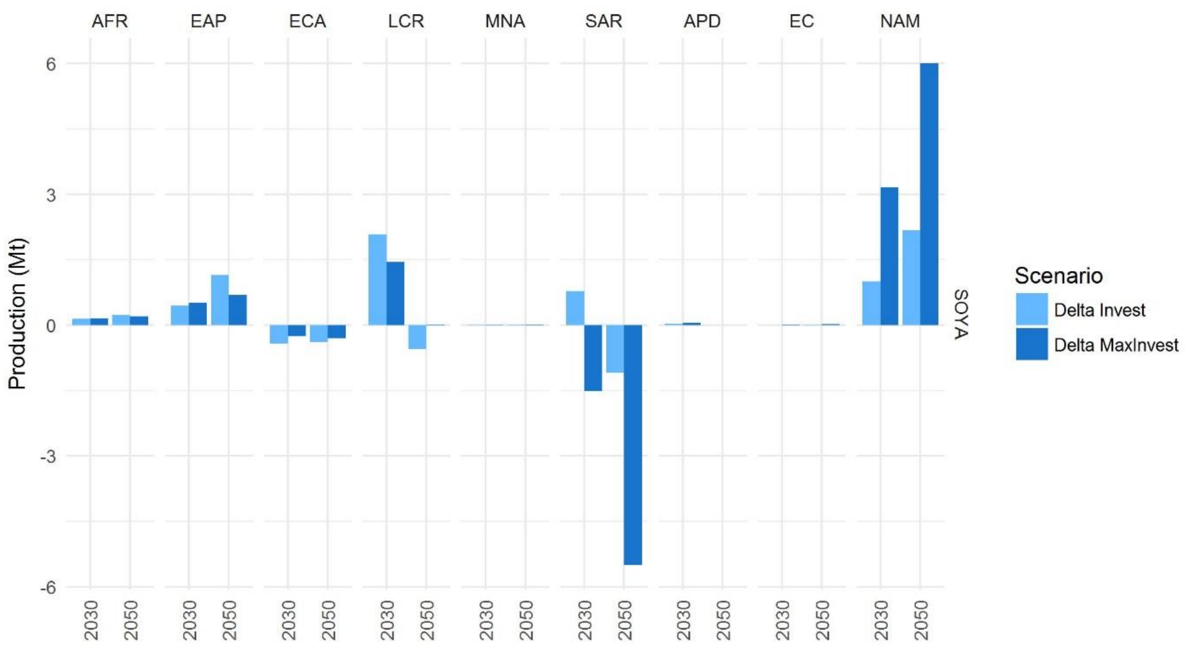

Figure SI 16. Difference in soybean production relative to *ZeroInvest* in 2030 and 2050 (Mt)

2.3.Land use change

By 2050 under *ZeroInvest* and *Invest*, cropland area expands by 181 Mha, while under *MaxInvest* cropland expands less (175 Mha). In *ZeroInvest*, 145 Mha of forest area are converted to agricultural land from 2010 to 2050. In *MaxInvest*, an additional 6 million more hectares of forest area are converted. 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 SI 17).

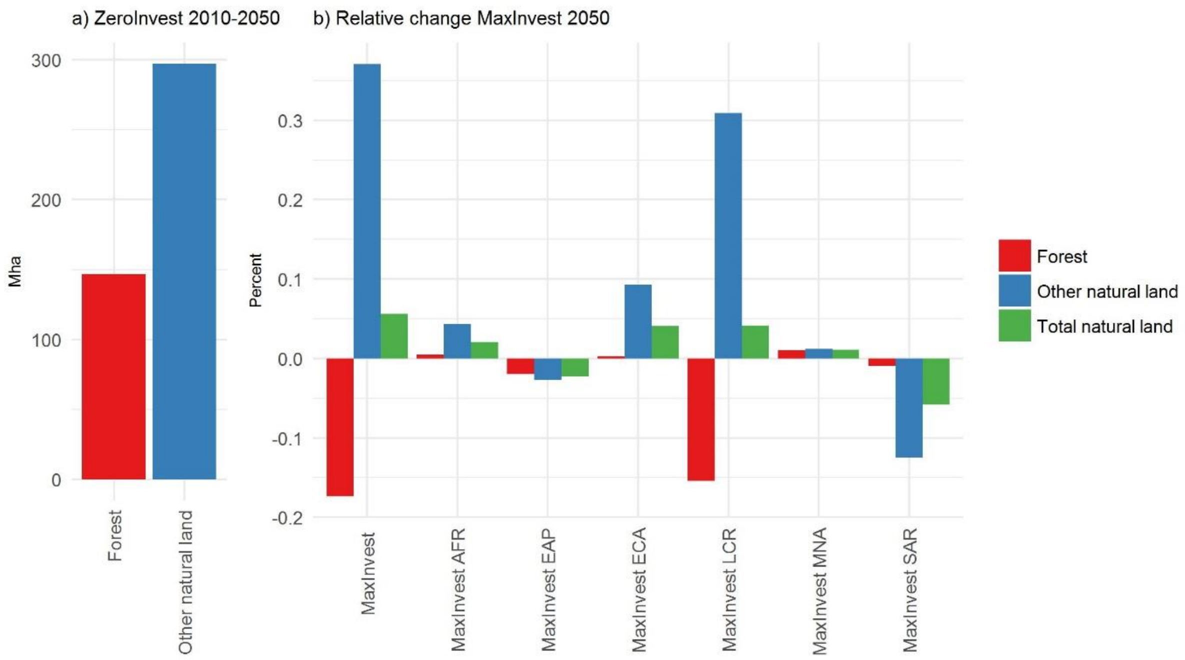

Figure SI 17. Hectares of forest area and natural land converted to cropland and grassland globally in 2050 under *ZeroInvest* (Mha) (left) and percent difference in hectares converted in 2050 from *ZeroInvest* for forest area and natural land (right)

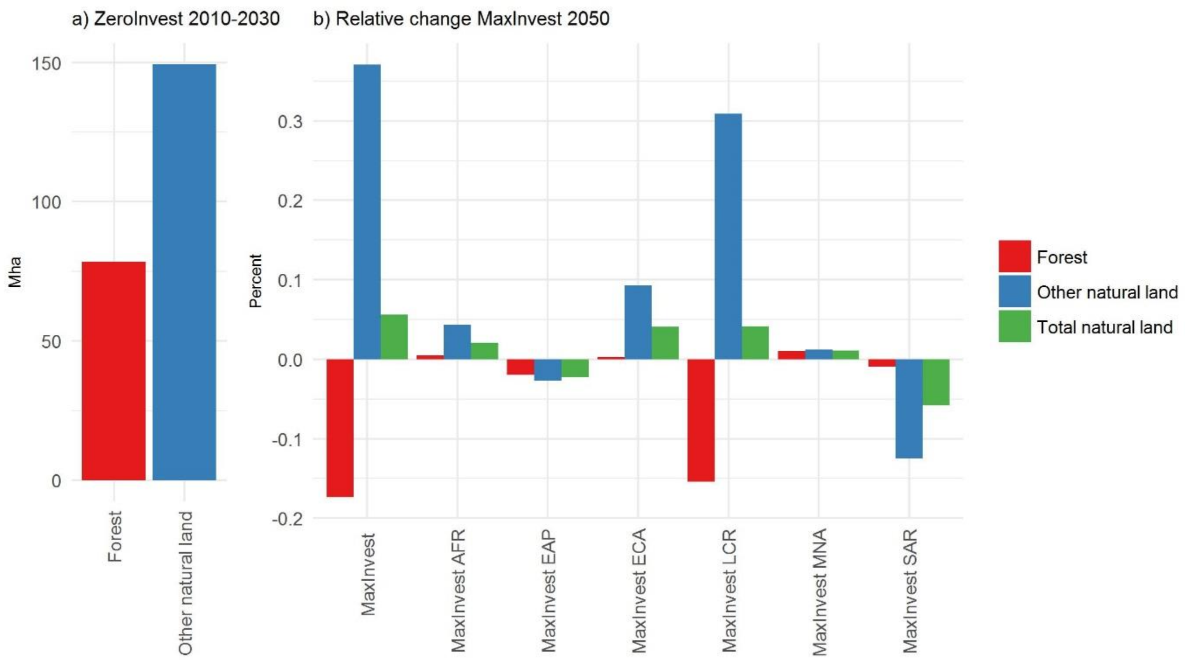

Figure SI 18. Hectares of forest area and natural land converted to cropland and grassland globally in 2030 under *ZeroInvest* (Mha) (left) and percent difference in hectares converted in 2030 from *ZeroInvest* for forest area and natural land (right)

Sub-Saharan Africa

The most forest and other natural land is converted in AFR (160 Mha, almost 36% of the total land converted in developing regions) in *ZeroInvest*, but in *MaxInvest* and AFR *MaxInvest*, the total quantity of land converted (forest and other natural land) is 1.8 and 1.3 Mha less than in *ZeroInvest* (Figure SI 19).

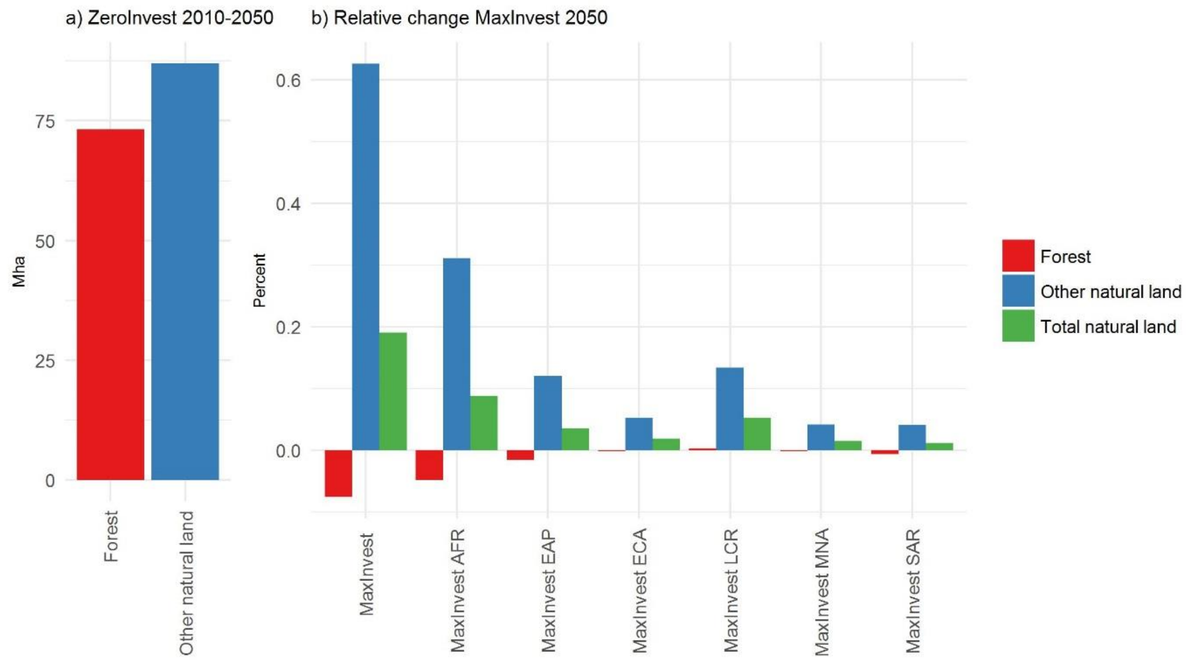

Figure SI 19. Forest and other natural land area converted to cropland and grassland in Sub-Saharan Africa in 2050 under *ZeroInvest* (Mha) (left) and percent difference in area converted in 2050 compared to *ZeroInvest* for forest and other natural land (right)

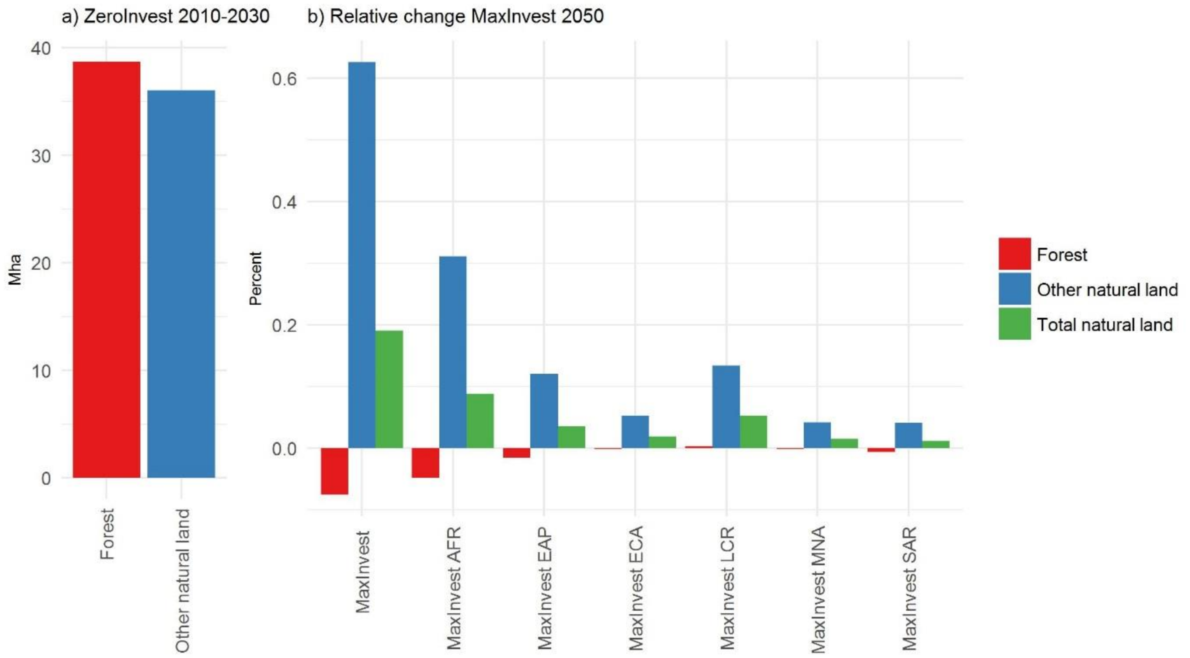

Figure SI 20. Hectares of forest area and natural land converted to cropland and grassland in Sub-Saharan Africa in 2030 under *ZeroInvest* (Mha) (left) and percent difference of hectares converted in 2030 compared to *ZeroInvest* for forest area and natural land (right)

East Asia and Pacific

The *MaxInvest* and EAP *MaxInvest* scenarios have the highest conversion of total area (forest and other natural land) (Figure SI 21). Although the total land converted in these scenarios is only 3 percent higher than the total conversion in *ZeroInvest*, the deforestation rate is 4-6% higher, implying that forest areas in EAP may be better-suited for irrigated area expansion.

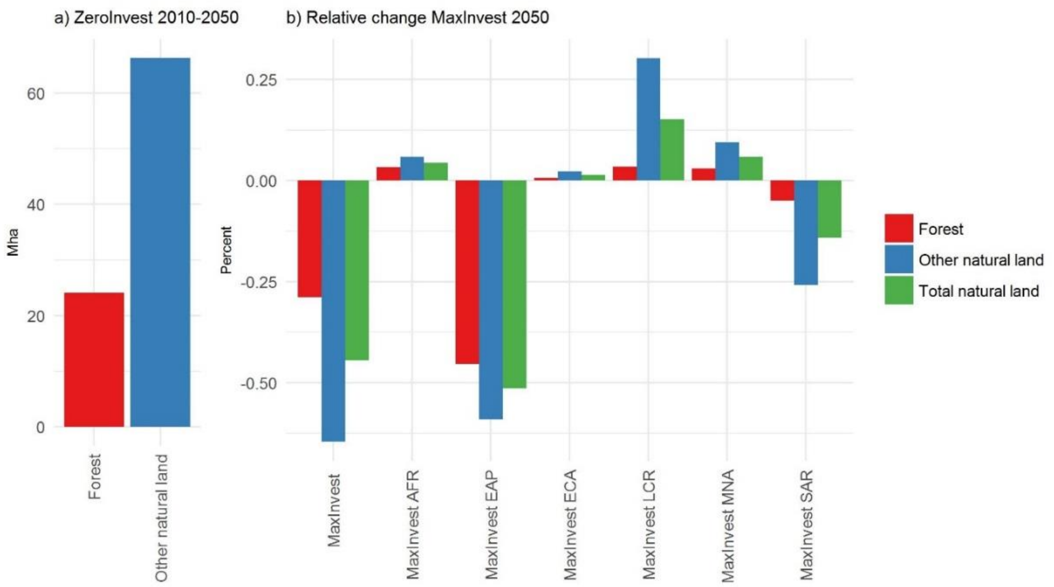

Figure SI 21. Forest and other natural land area converted to cropland and grassland in East Asia and Pacific in 2050 under ZeroInvest (Mha) (left) and percent difference in area converted in 2050 compared to Invest for forest area and other natural land (right)

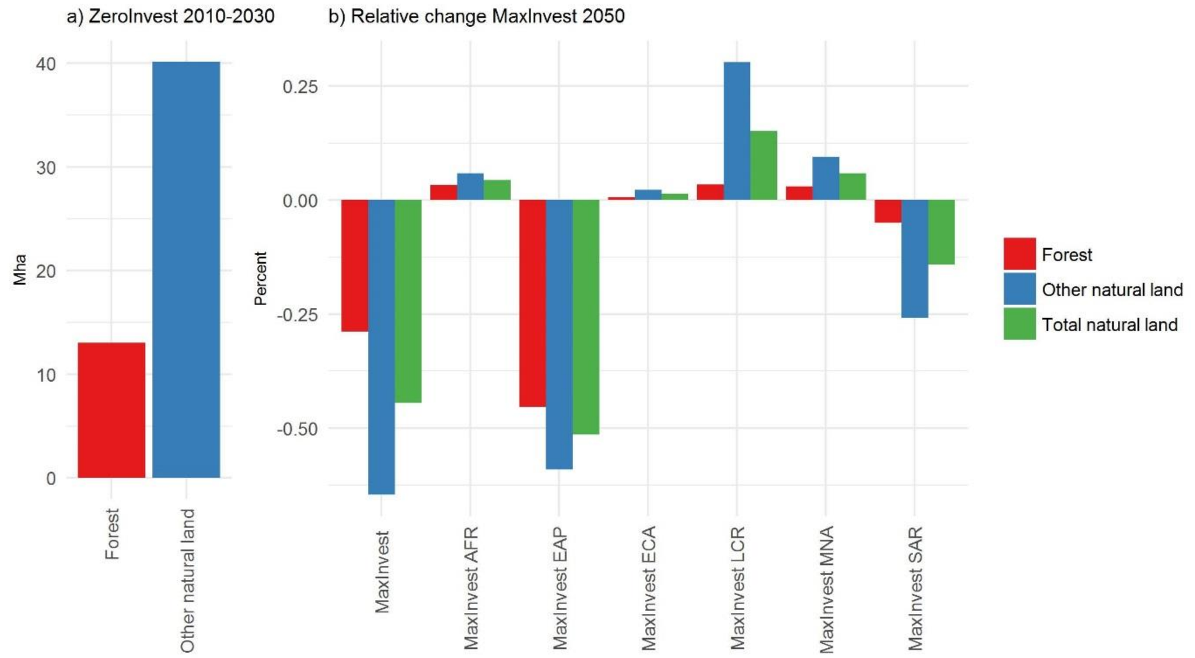

Figure SI 22. Hectares of forest area and natural land converted to cropland and grassland in East Asia and Pacific in 2030 under *ZeroInvest* (Mha) (left) and percent difference of hectares converted in 2030 compared to *Invest* for forest area and natural land (right)

Europe and Central Asia

Relative to *ZeroInvest*, all investment scenarios decrease the land converted in ECA in 2050, although only for natural land as no forest land is converted. The *MaxInvest* and ECA *MaxInvest* scenarios have the lowest conversion of natural land compared to *ZeroInvest*, (8-6% less in 2050) (Figure SI 23).

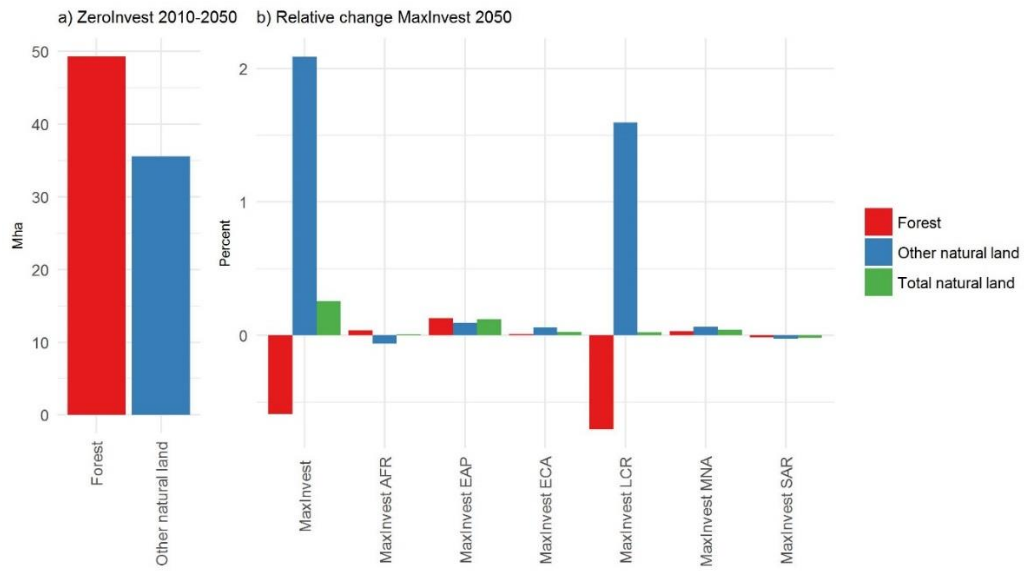

Figure SI 23. Forest and other natural land area converted to cropland and grassland in Europe and Central Asia in 2050 under *ZeroInvest* (Mha) (left) and percent difference in area converted in 2050 compared to *Invest* for forest and other natural land (right)

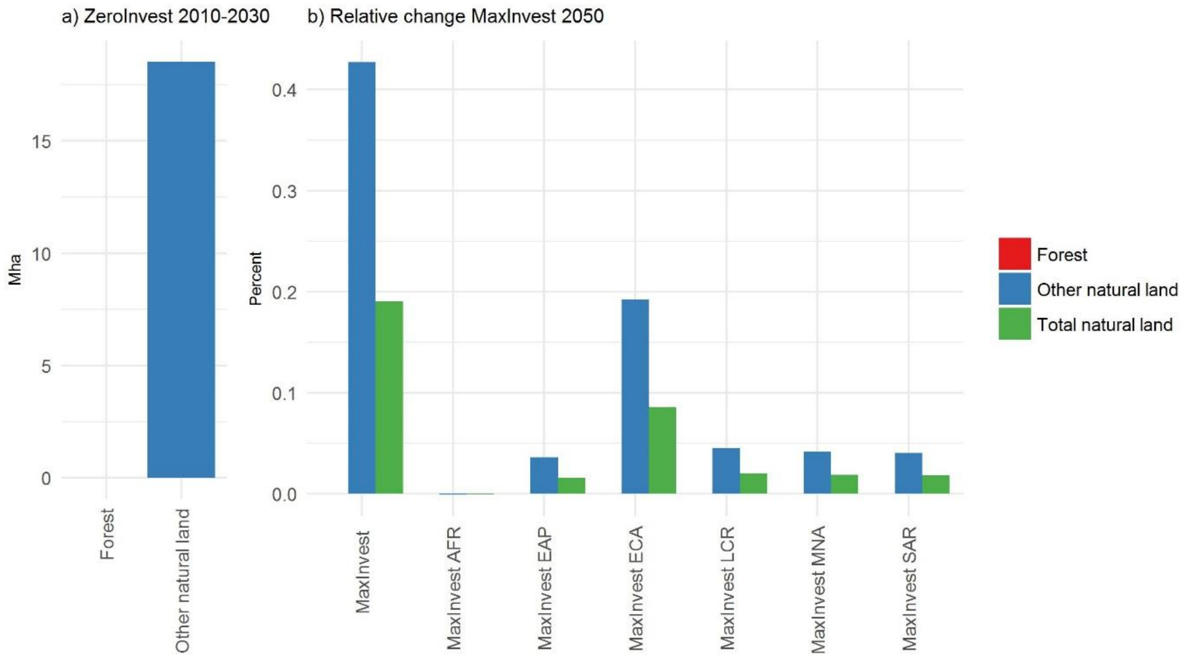

Figure SI 24. Hectares of forest area and natural land converted to cropland and grassland in Europe and Central Asia in 2030 under *ZeroInvest* (Mha) (left) and percent difference of hectares converted in 2030 compared to *Invest* for forest area and natural land (right)

Latin America and Caribbean

Although *MaxInvest* and LCR *MaxInvest* have greater deforestation in 2050 compared to *ZeroInvest*, less overall area (forest and natural land) is converted in all scenarios compared to *ZeroInvest* (Figure SI 25).

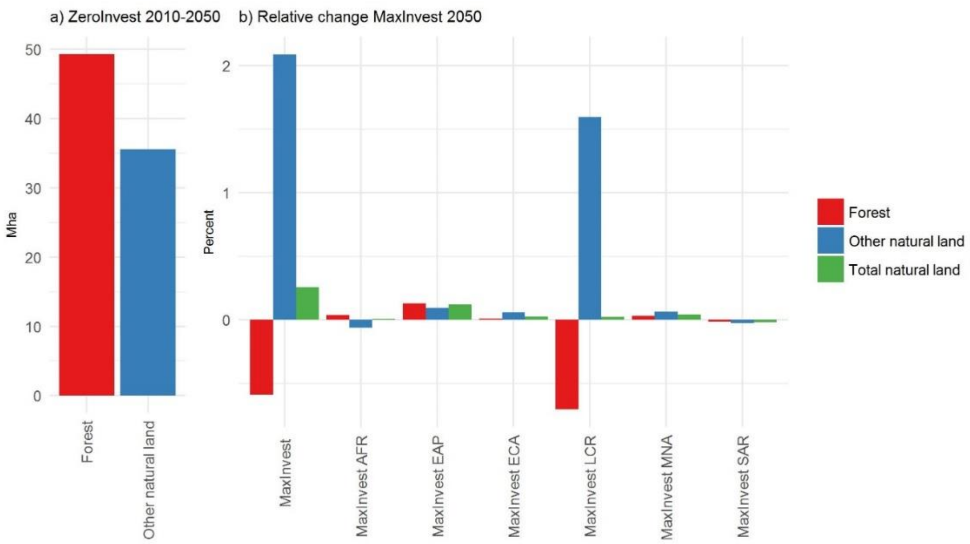

Figure SI 25. Forest area and other natural land area converted to cropland and grassland in Latin America and Caribbean in 2050 under *ZeroInvest* (Mha) (left) and percent difference in area converted in 2050 compared to *Invest* for forest and other natural land (right)

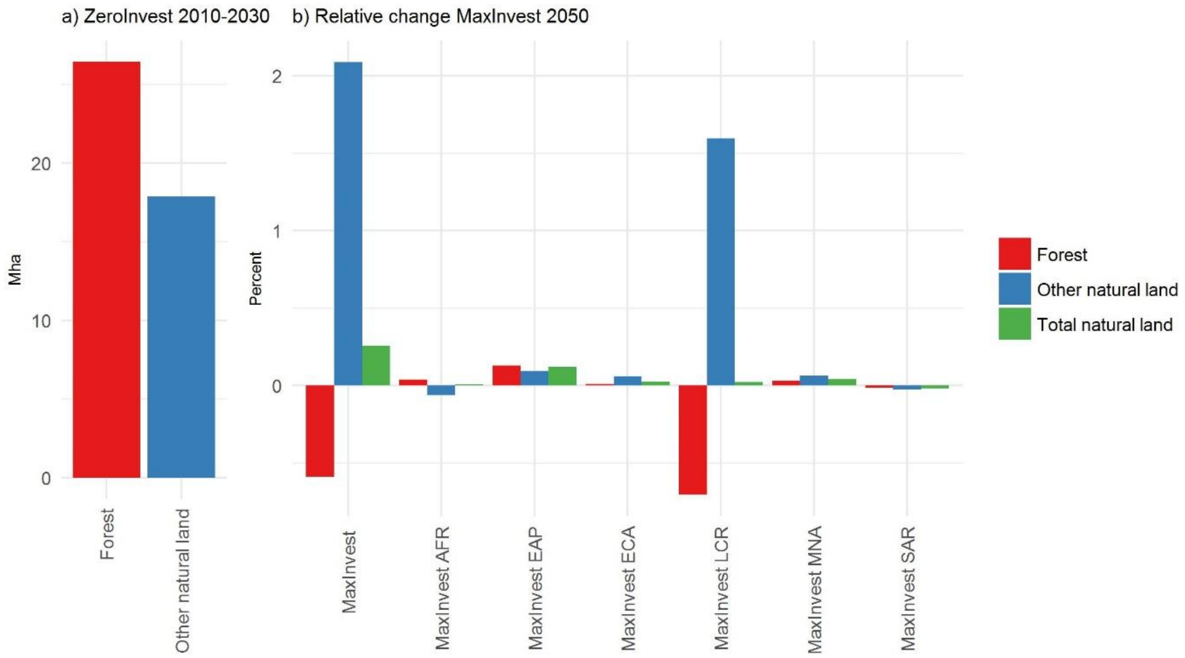

Figure SI 26. Hectares of forest area and natural land converted to cropland and grassland in Latin America and Caribbean in 2030 under *ZeroInvest* (Mha) (left) and percent difference of hectares converted in 2030 compared to *Invest* for forest area and natural land (right)

Middle East and North Africa

All investment scenarios increase the land converted in MNA, although only for natural land. The *Invest*, *MaxInvest* and MNA *MaxInvest* scenarios have the lowest conversion of natural land (Figure SI 27).

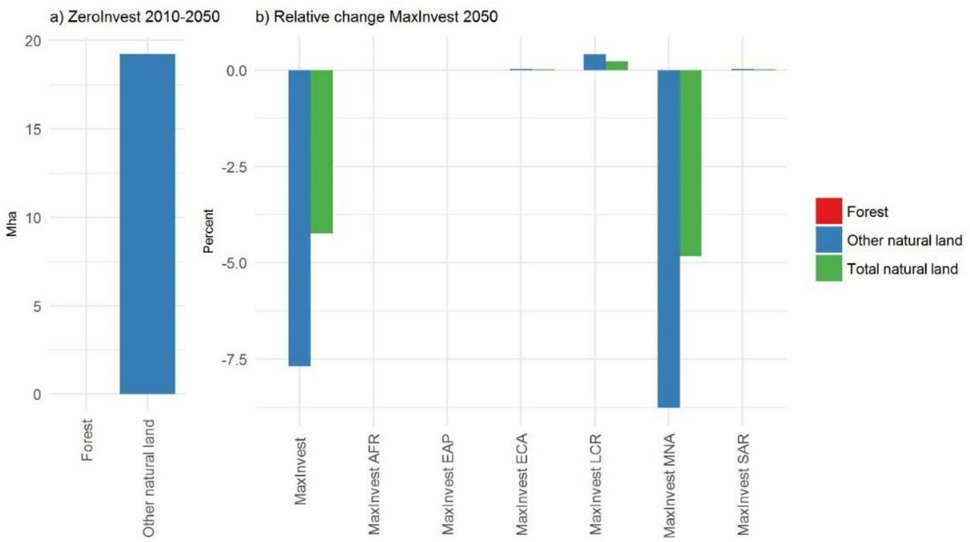

Figure SI 27. Forest and other natural land area converted to cropland and grassland in Middle East and North Africa in 2050 under *ZeroInvest* (Mha) (left) and percent difference in area converted in 2050 compared to *Invest* for forest and other natural land (right)

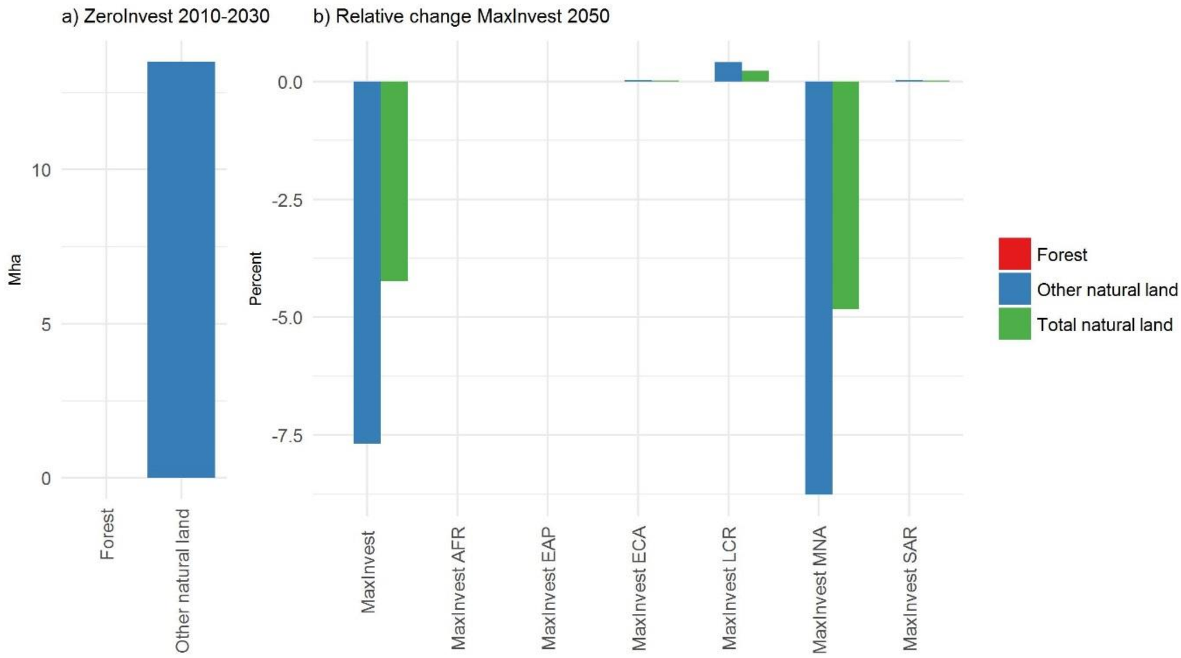

Figure SI 28. Hectares of forest area and natural land converted to cropland and grassland in Middle East and North Africa in 2030 under *ZeroInvest* (Mha) (left) and percent difference of hectares converted in 2030 compared to *Invest* for forest area and natural land (right)

South Asia

All investment scenarios increase the land converted in SAR. The *MaxInvest* and SAR *MaxInvest* scenarios have the highest conversion of total area (forest and natural land), and *Invest* has the least additional area converted in 2050 compared to *ZeroInvest*. There is very little forest area converted in general in all the scenarios, however 218,000 ha of forest land is converted the *MaxInvest* and SAR *MaxInvest*, implying that forest areas are the most well-suited for irrigated area expansion (Figure SI 29).

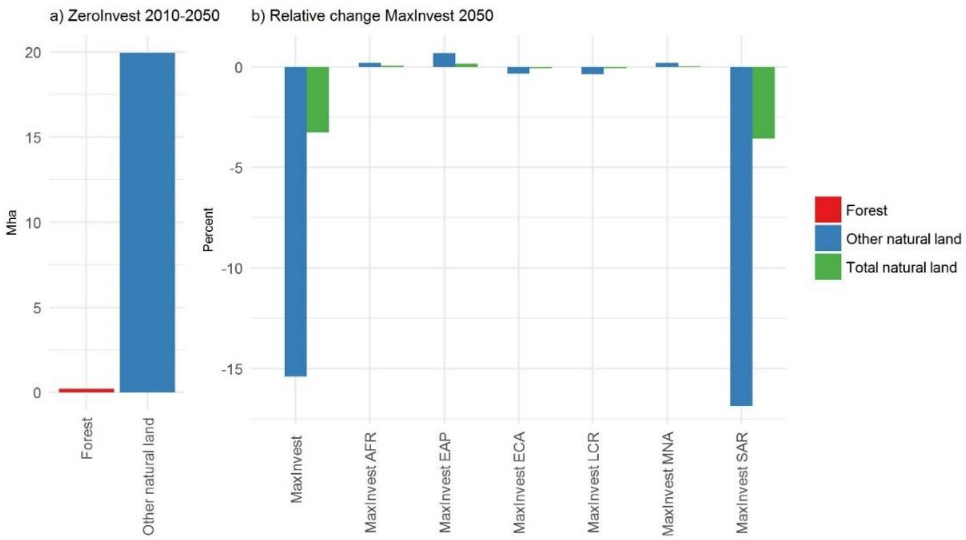

Figure SI 29. Forest and other natural land area converted to cropland and grassland in South Asia in 2050 under *ZeroInvest* (Mha) (left) and percent difference in area converted in 2050 compared to *Invest* for forest and other natural land (right)

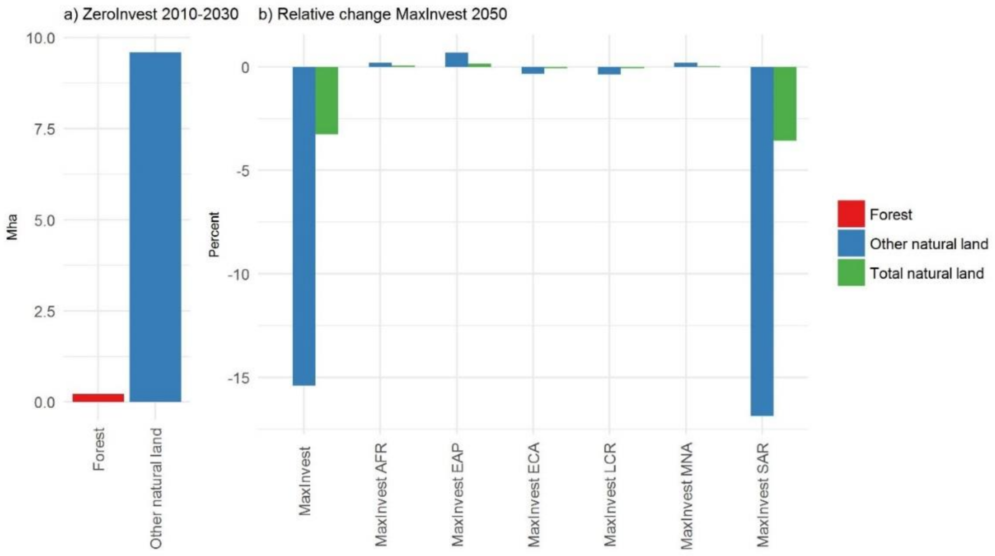

Figure SI 30. Hectares of forest area and natural land converted to cropland and grassland in South Asia in 2030 under *ZeroInvest* (Mha) (left) and percent difference of hectares converted in 2030 compared to *Invest* for forest area and natural land (right)

2.4.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* (Figure SI 31).

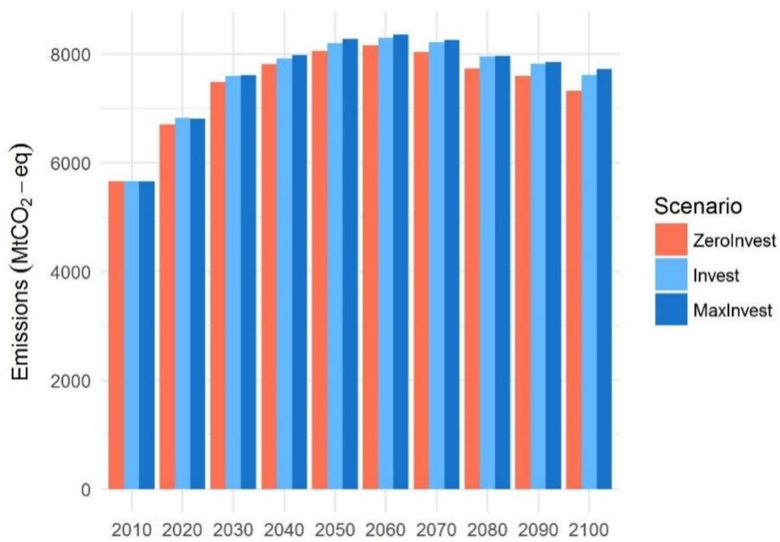

Figure SI 31. Greenhouse gas emissions from crop and livestock production and land use change from 2010-2100 (Mt CO2 eq)

Sub-Saharan Africa

GHG emissions from land use, land use change, and forestry over the period 2010-2015 increase dramatically in AFR (about 75% higher than 2010 levels), although most of the increase in LULUCF emissions come from land use change and livestock production, more specifically from deforestation and conversion of natural land for cropland and grassland. However, the overall land use change trend occurs in all investment scenarios. There is only a slightly less deforestation and conversion of land in *MaxInvest*.

East Asia and Pacific

In 2010, EAP was the largest contributor to LULUCF emission (25% of the total LULUCF GHG emissions) and by 2050, in all investment strategies EAP remains the largest contributor (27% of the total LULUCF GHG emissions). Under different investment scenarios, LULUCF GHG emissions increase (between 60-68 Mt CO_2 eq higher than *ZeroInvest* in 2050). In *Invest*, nearly 60% of the additional GHG emissions come from livestock production, about 30% from crop production and the remaining from land use change and methane emissions from rice production. Most notably is that of the additional GHG emissions compared to *ZeroInvest*, the land use change share of the additional emissions increases to almost 30% under the regional *MaxInvest* scenario due to the expansion of irrigated cropland.

Europe and Central Asia

LULUCF GHG emissions increase 28% from 2010 to 2050 in *ZeroInvest*. Most of these new emissions come from livestock production (61% of the total increase in GHG emissions from 2010-2050), but 32 percent come from crop production. Under different investment scenarios, LULUCF GHG emissions increase (between 5-7 Mt CO_2 eq higher than *ZeroInvest* in 2050), nearly all from increased crop production.

Latin America and Caribbean

In 2010, LCR contributed almost 20% of the LULUCF GHG emissions, about 75% from livestock production and 20% from land use change. By 2050, under *ZeroInvest* LULUCF GHG emissions increase 35%, with 47% of the additional emissions coming from livestock production and almost 40% from land use change. Under different investment scenarios, LULUCF GHG emissions increase (between 8 - 102 Mt CO_2 eq higher than *ZeroInvest* in 2050). In the *Invest* scenario where emissions are only 2% higher than *ZeroInvest*, 55% of the additional emissions in 2050 come from land use change, 30% from crop production and 20% from additional livestock production. In *MaxInvest*, of the additional emissions 102 Mt CO_2 eq, nearly 85% of the come from land use change and 10% from additional crop production. The regional *Invest* scenario has emissions nearly as high as the *MaxInvest*, 25% more emissions in 2050 compared to *ZeroInvest*.

Middle East and North Africa

In 2010, MNA contributed only 3% of the LULUCF emission, 67% from livestock production and 25% from crop production. By 2050, under *ZeroInvest* the LULUCF GHG emissions increase 27%, with the additional emissions coming from livestock production and emissions from crop production. Increased emissions from rice and crop production in the investment scenarios increase the GHG emissions in 2050 by about 4%.

South Asia

In 2010, SAR contributed 15% of the global LULUCF emission, 67% from livestock production and 14% from crop production and 17% from methane released during rice production. By 2050, under *ZeroInvest* the LULUCF GHG emissions increase 36%, with the additional emissions coming from livestock production (63% of the additional emissions) and emissions from crop production (27% of the additional emissions). In *Invest*, *MaxInvest*, and Region *Invest*, the additional emissions from crop production and additional emissions from livestock scenarios result in overall LULUCF GHG emissions that are 25% higher than *ZeroInvest* in 2050.

2.5. Water withdrawal

Water withdrawals for domestic and industrial users are expected to increase 40% by 2020 and nearly double by 2050, however, irrigation will continue to be the largest user of water (Figure SI 32).

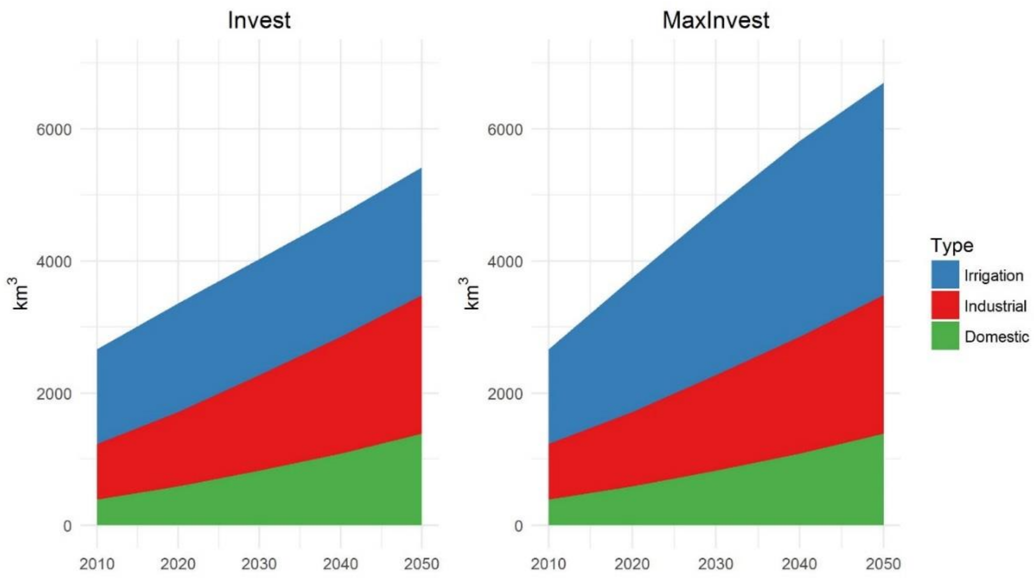

Figure SI 32. Global water withdrawals for irrigation, domestic and industrial users in *Invest* and *MaxInvest* from 2010-2050 (km3)

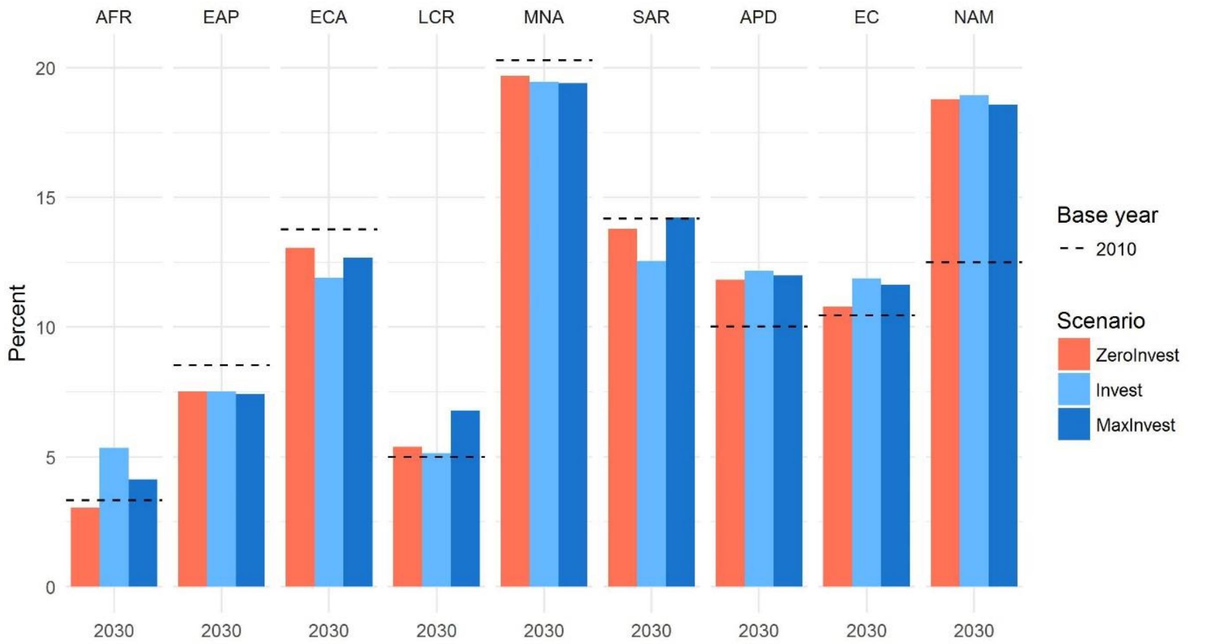

Figure SI 33. Surface water withdrawals for irrigation considered unsustainable as a share of the total surface water withdrawal for irrigation by region in 2030 (%)

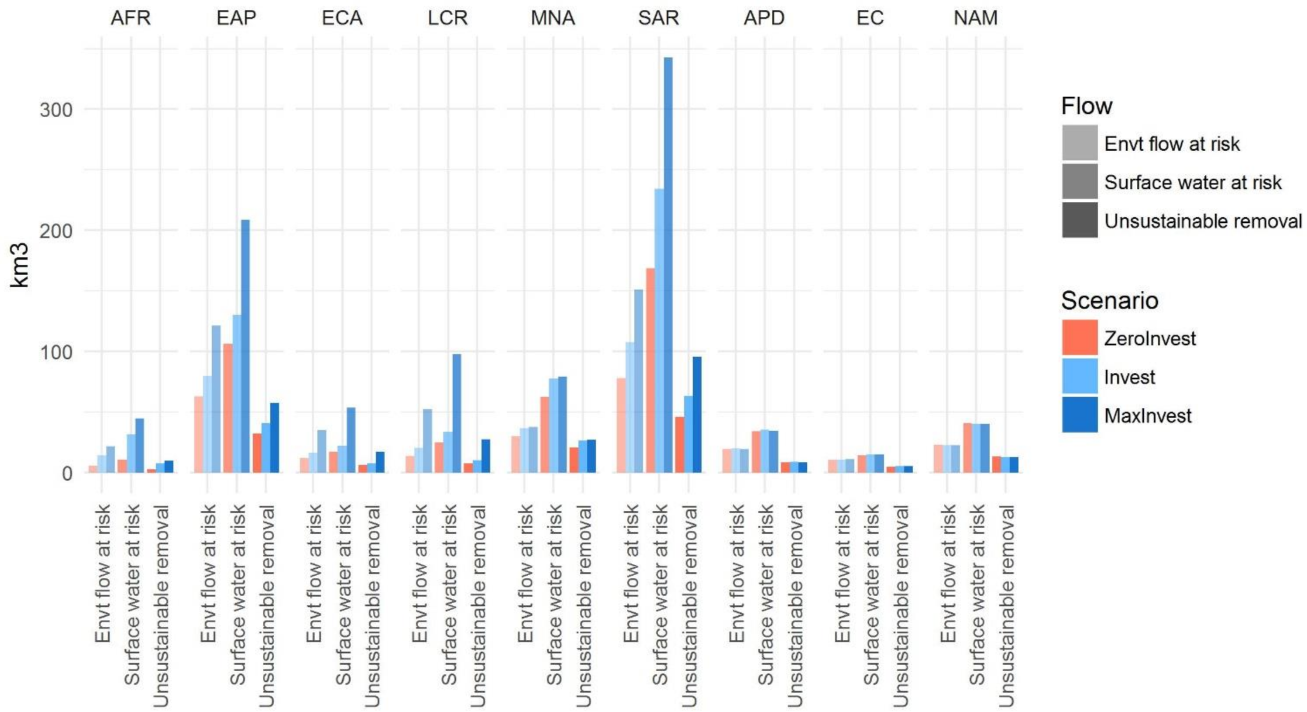

Figure SI 34. Comparison of surface water withdrawals considered unsustainable ("Unsustainable removal"), irrigation surface water withdrawals taking place in locations at risk for unsustainable withdrawal ("Surface water at risk"), environmental flow at risk by irrigation ("Envt flow at risk") in 2030 (km3)

3. Detailed regional results

In the following sections 3.1 to 3.6, we discuss of the impacts of irrigation investments on each World Bank region.

3.1. Sub-Saharan Africa

FAO estimates that 35 Mha of cropland could be irrigated in Sub-Saharan Africa and in 2010, about 5.9 Mha of cropland were irrigated (FAO, 2017; Frenken, 2005). Without investment, irrigated areas decline by 1 Mha by 2050 due to the lack of investment in infrastructure which increases the price for water used for irrigation (*ZeroInvest*). Under the moderate *Invest* scenario, by 2050 irrigated area is 175% higher than under *ZeroInvest* (130% higher than 2010 levels) (Figure SI 35). Under *MaxInvest* and Region *MaxInvest* irrigated area is more than 460% higher than *ZeroInvest* (adding about 22 Mha of irrigated cropland), hence depending on the scenario 39 to 79% of the potentially irrigable area would actually be equipped. Water demand for irrigation increases significantly under the investment scenarios, but less proportionally than the irrigated area expansion because the compositions of the new irrigated area is in more efficient irrigation systems than in 2010. Under all the investment scenarios there is less expansion of rainfed area (7 to 24 Mha less) compared to *ZeroInvest*, and in *MaxInvest* this leads to less cropland area needed in 2050 by about 1.3 Mha. Compared to *ZeroInvest*, crop production in 2050 under the investment scenarios is lower due to the changes in the crops grown in the region under investment- more of rice, millet, potatoes, and groundnuts and less of cassava, sugar cane, corn, sorghum and wheat. Consumption is slightly higher in the investment scenarios in 2050 compared to *ZeroInvest*. Under the irrigation investment strategies, the share of domestic consumption of all crops coming from imports increases. However, for crops like rice, which accounts for 11% of total quantity of crops consumed in the region, 38% of the rice consumed is imported in *ZeroInvest*, though under the irrigation investment scenarios that share decreases to 33%. While irrigated area expands significantly, the average crop yields decline though this can signal a shift between different crops grown. There is marginal impact on food security under the investment scenarios or land use change except for slightly more natural land converted under the investment scenarios. GHG emissions from agriculture, forestry, and other land use change (AFOLU) [1] over the period 2010-2050 increase dramatically in AFR (about 75% higher than 2010 levels), with most of the increase in AFOLU emissions coming from land use change and livestock production, more specifically from deforestation and conversion of natural land to cropland and grassland. However, the overall land use change trend occurs in all investment scenarios. On average, the irrigation infrastructure investments in the *Invest* scenario would cost about \$4.3 billion per year over 40 years, and \$10.7 billion per year over 40 years in *MaxInvest*, and \$11.5 billion per year over 40 years in Region *MaxInvest*. Most of these costs would be in expansion and depreciation but some costs associated with the upgrade of irrigation systems to more efficient systems would also be incurred (Figure SI 37). This investment returns an additional 0.5% improvement in food security, 1% decrease in AFOLU GHG emissions, about 1% less cropland area needed, and 3% less conversion of natural lands by 2050. However, the tradeoffs to irrigation investments should be considered, such as the impact of increased water withdrawal on environmental flow. The share of unsustainable surface water withdrawn for irrigation, water that should be left for the environment, increases under the most ambitious investment scenario from 3% of the total surface water withdrawn in 2010 to 7% of the total surface water withdrawn in 2050 while the share of the total irrigation withdrawals at risk to become

[1] Emissions covered by GLOBIOM include the CO_2 emissions from land use change (deforestation and conversion of natural land) and non-CO_2 emissions from crop production, livestock, and fertilizer application

unsustainable increases from 13% in 2010 to 33.6% of the total withdrawal of water for irrigation in 2050.

The uncertainty of these results is in terms of irrigated area expansion under *Invest* is +8/-24% and +15/-71% for *MaxInvest*.

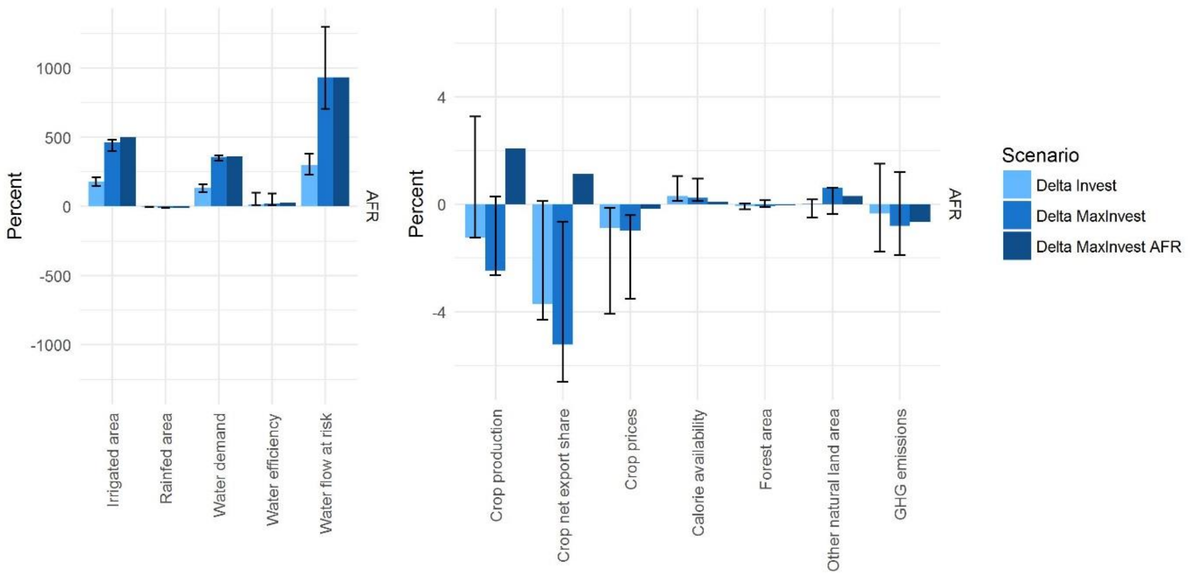

Figure SI 35. Summary of percent difference between investment scenarios and *ZeroInvest* in 2050 for various indicators in the Sub-Saharan Africa Region

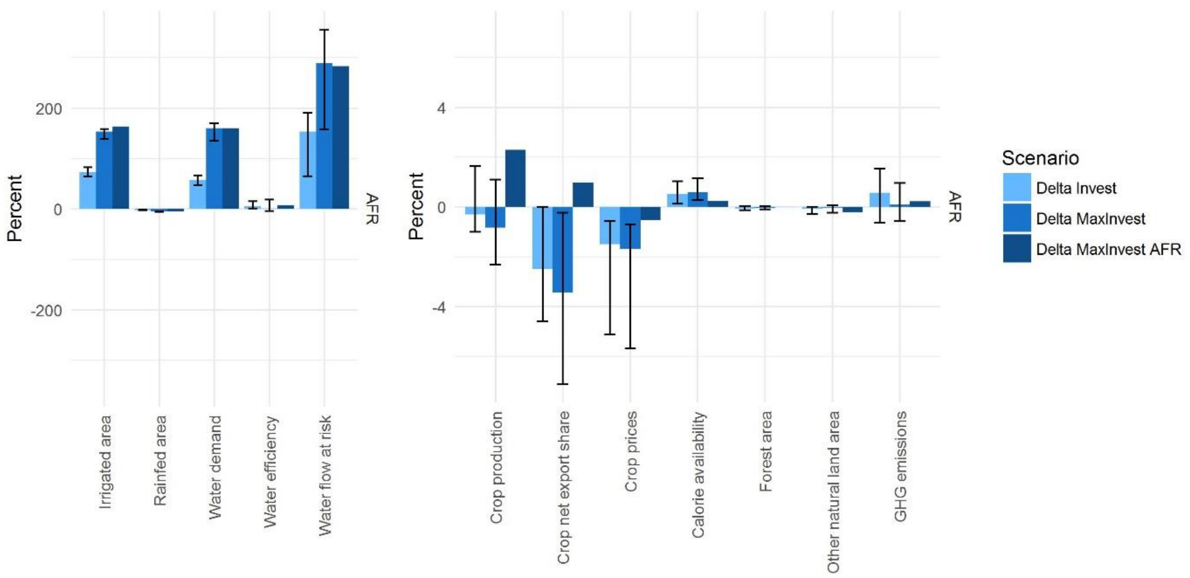

Figure SI 36. Summary of percent difference between investment scenarios and ZeroInvest in 2030 for various indicators in the Sub-Saharan Africa Region.

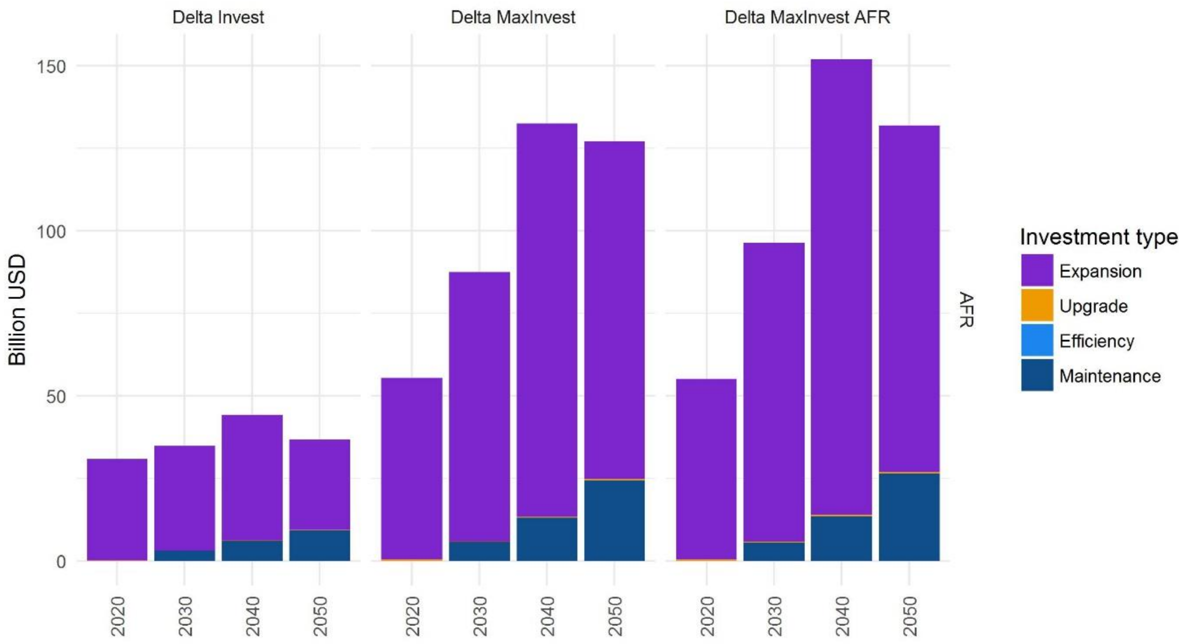

Figure SI 37. Summary of additional irrigation investment scenarios for Sub-Saharan Africa needed from 2020-2050 region compared to *ZeroInvest* ($ billion, 2000 US dollar)

3.2. East Asia and Pacific

FAO estimates that 119 Mha of cropland could be irrigated in East Asia and the Pacific, and in 2010 approx. 87 Mha were already irrigated (FAO, 2017; Frenken, 2011). Without investment in irrigation infrastructure, the water price increases leading to a decrease in irrigated areas by almost 19 Mha by 2050 (*ZeroInvest*). Irrigated area is about 20% higher than 2010 levels by 2050 under *Invest*, with an expansion of nearly 18 Mha (*Invest*). Both *MaxInvest* and Region *MaxInvest* scenarios have 70% more irrigated area in 2050 than *ZeroInvest* in 2050 (adding about 30 Mha) (Figure SI 38). Depending on the scenario 88%-99% of the potentially irrigable area would be equipped by 2050. Under ambitious investment, the withdrawal of water for irrigation would increase more than 50% from 2010 levels. Although there would be between 35 and 49 Mha less rainfed area under the investment scenarios by 2050, overall crop area is about 1.5 to 1.6 Mha more than *ZeroInvest*. Crop production is 3% higher under *Invest* (+34 Mt dm), 5% higher under *MaxInvest* (+61 Mt dm), and 6% higher under Region *MaxInvest* (+76 Mt dm), compared to *ZeroInvest* in 2050. Consumption increases under the investment scenarios (14 to 35 more kcal per capita per day in 2050) due to the slightly lower crop prices. In 2050 under *ZeroInvest*, EAP is a net importer, but under the investment scenarios the region imports significantly less and nearly has an equal trade balance in Region *MaxInvest*. Additional agricultural area is needed under different investment scenarios compared to *ZeroInvest* by 2050 resulting in AFOLU GHG emissions that are about 3% higher. Depreciation costs under *ZeroInvest* are about $4.7 billion per year over 40 years (Figure SI 40). Costs for the *Invest* scenario are an additional $6.4 billion per year, $16 billion per year under *MaxInvest*, and $11.3 billion per year under the Region *MaxInvest*. Investments in irrigation result in 6% more in kilocalories available, 5% more crop production, and balanced trade. Irrigation investments and the subsequent expansion in irrigated area increase water withdrawals by almost 80% by 2050 compared to *ZeroInvest* scenario.

The uncertainty of these results is in terms of irrigated area expansion under *Invest* is +14/-3% and +16/- 7% for *MaxInvest*.

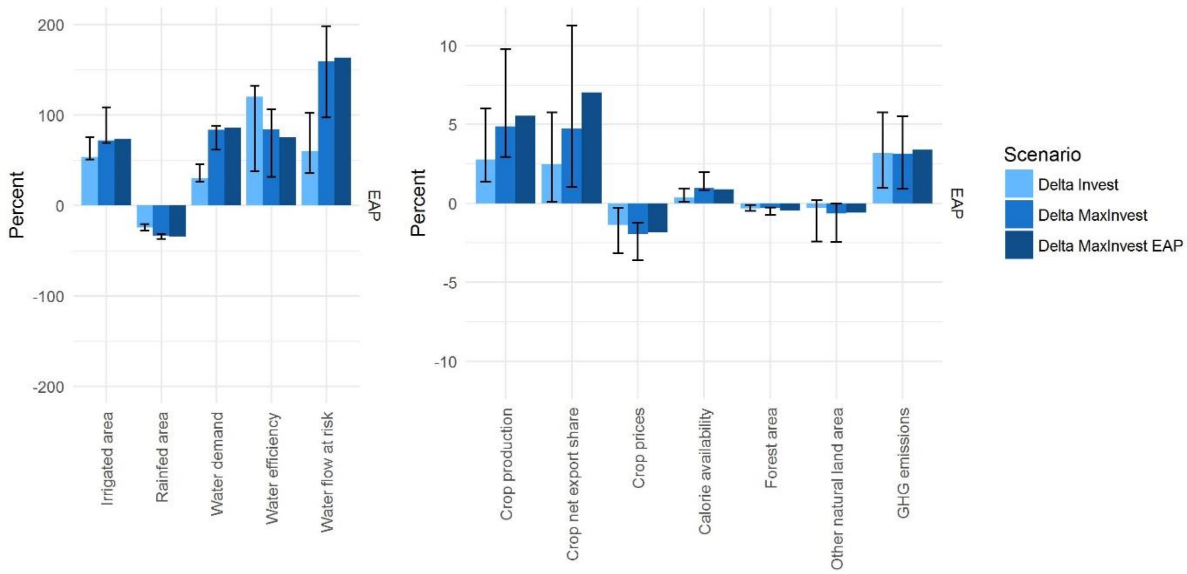

Figure SI 38. Summary of percent difference between investment scenarios and *ZeroInvest* in 2050 for various indicators in East Asia and Pacific Region

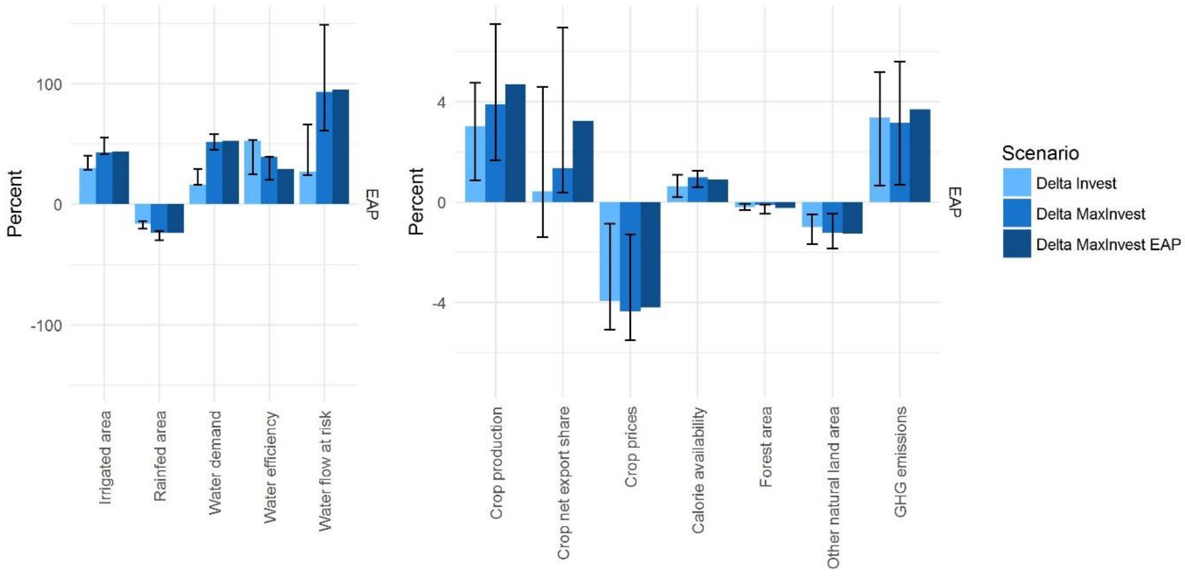

Figure SI 39. Summary of percent difference between investment scenarios and ZeroInvest in 2030 for various indicators in the East Asia and Pacific Region.

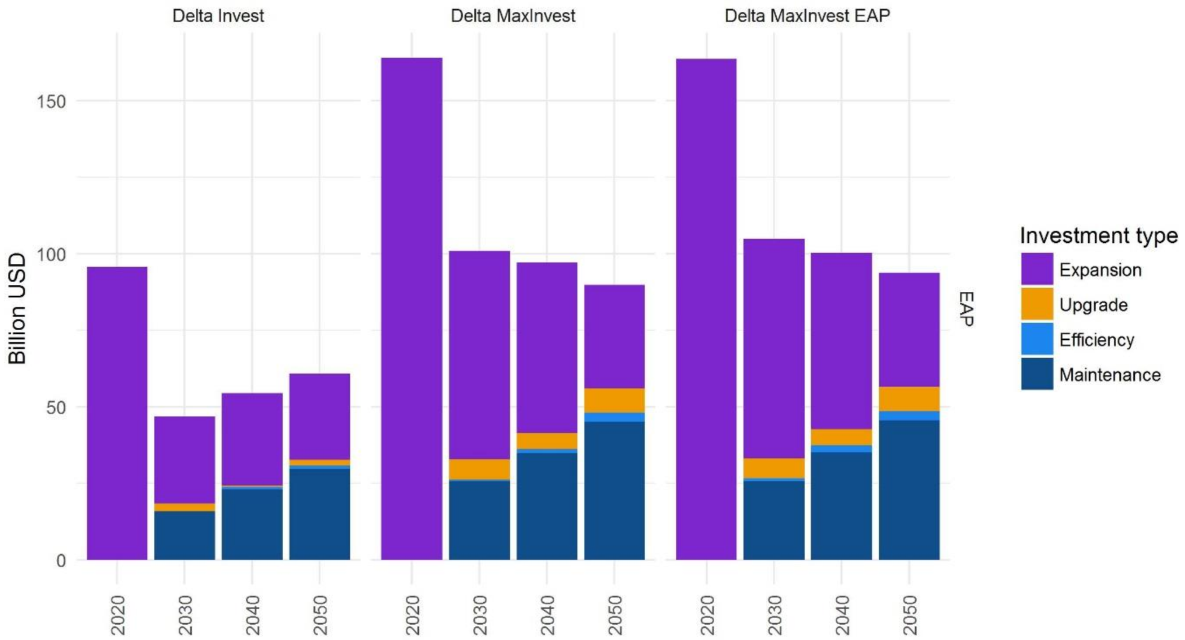

Figure SI 40. Summary of additional irrigation investment scenarios needed for the East Asia and Pacific region from 2020-2050 region compared to *ZeroInvest* ($ billion, 2000 US dollar)

3.3. Europe and Central Asia

FAO estimates that 69 Mha of cropland could be irrigated in Europe and Central Asia, and in 2010 approx. 11 Mha were already irrigated (FAO, 2017; Frenken, 2013). Without investment in irrigated infrastructure the water price for irrigation increases which would cause nearly 40% of irrigated areas would be converted back to rainfed areas or abandoned as cropland. Under the *Invest* scenario irrigated areas would expand 8% from 2010 levels (75% higher than *ZeroInvest*), while water withdrawals for irrigation decrease 4% from 2010 levels (Figure SI 41). Irrigation systems become more efficient due the upgrade of existing irrigated areas from surface systems to drip and sprinkler systems (nearly 50% more efficient in *Invest* and 72% more efficient in *MaxInvest*). Under *MaxInvest* and Region *MaxInvest* irrigated areas would increase nearly 120% from 2010 levels (+14 Mha), which corresponds to 36% of the potentially irrigable area. There would be 6 to 22 Mha less rainfed are under the investment scenarios in 2050 compared to *ZeroInvest* and total cropland area is about 4 Mha less in *MaxInvest* by 2050. Producing more on less land under the investment scenarios implies that irrigated areas intensify cropland use and are land sparing in the region. Under the investment scenarios, the region produces 3.5 Mt dm more under *Invest*, 9.0 Mt dm more under *MaxInvest*, and 18.5 Mt dm more under Region *MaxInvest* compared to *ZeroInvest* in 2050, producing more corn, and rapeseed and less barley and wheat. Consumption and calorie availability increase relative to *ZeroInvest* along with relatively lower crop prices. 3.1 Mha of natural land is spared from conversion for cropland and grasslands by 2050 compared to *ZeroInvest*. AFLOU GHG emissions increase 28% from 2010 to 2050 in *ZeroInvest*, and most of these new emissions come from livestock production and crop production. Under different investment scenarios, AFOLU GHG emissions are 1% higher than *ZeroInvest* in 2050. Depreciation costs under *ZeroInvest* are about $0.6 billion per year (Figure SI 43). The expansion and upgrade of systems in *Invest* would require an additional $0.8 billion per year. For the massive expansion in *MaxInvest* and Region *MaxInvest*, an additional $4.7 billion per year over 40 years is required. The investments in irrigation help to spare more than 3 Mha in natural lands from conversion, significantly increase the water productivity of irrigated areas, and produce 2% more crop products.

The uncertainty of these results is in terms of irrigated area expansion under *Invest* is +67/-41% and +156/-78% for *MaxInvest*.

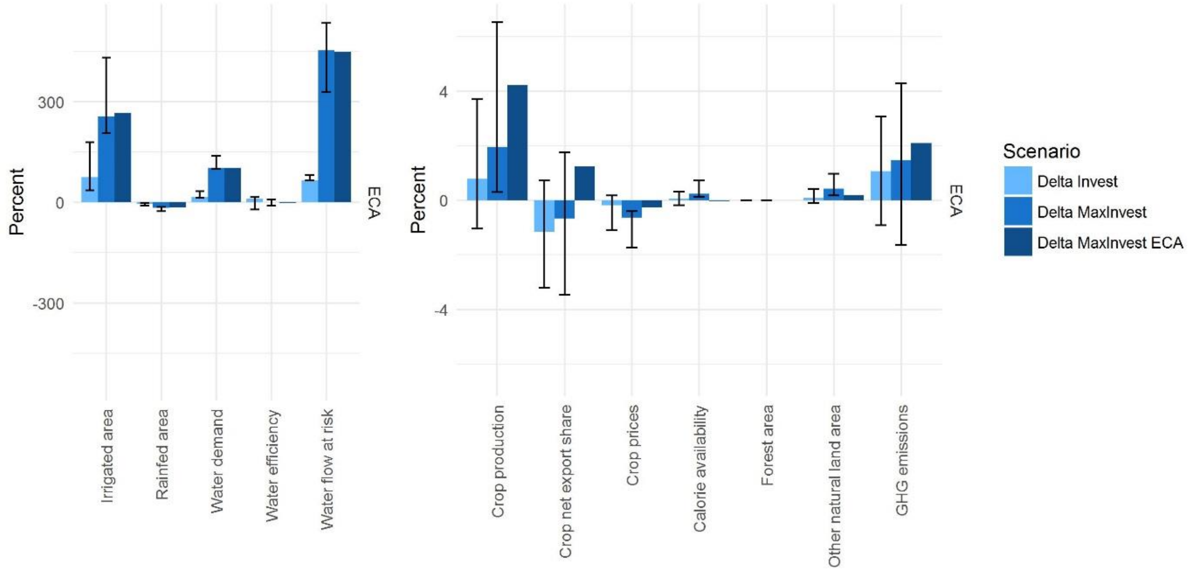

Figure SI 41. Summary of percent difference between investment scenarios and *ZeroInvest* in 2050 for various indicators in Europe and Central Asia

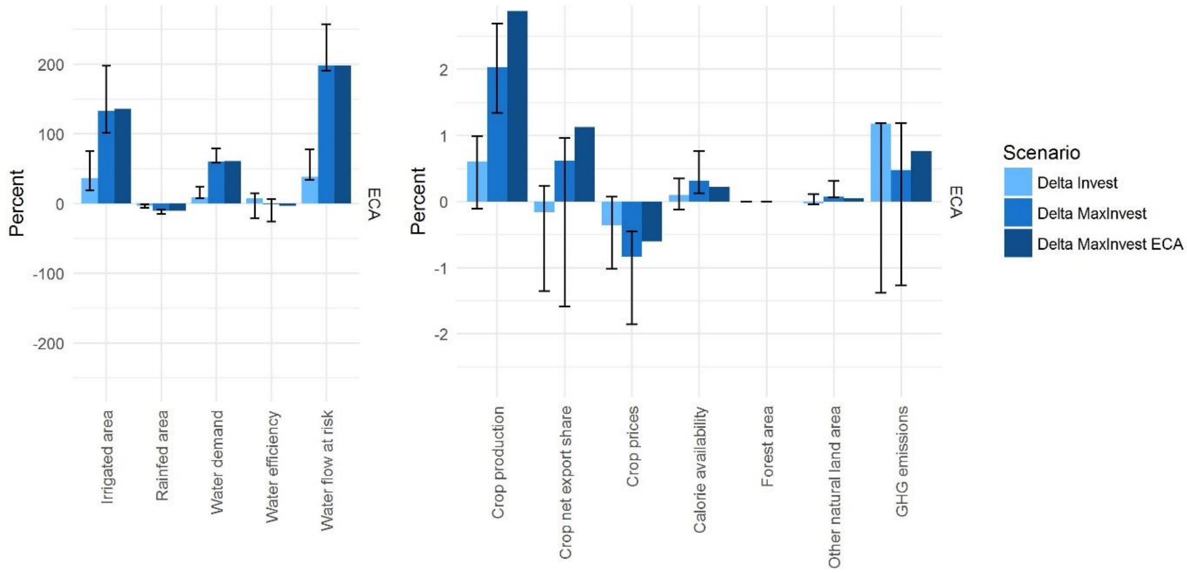

Figure SI 42. Summary of percent difference between investment scenarios and ZeroInvest in 2030 for various indicators in the Europe and Central Asia region.

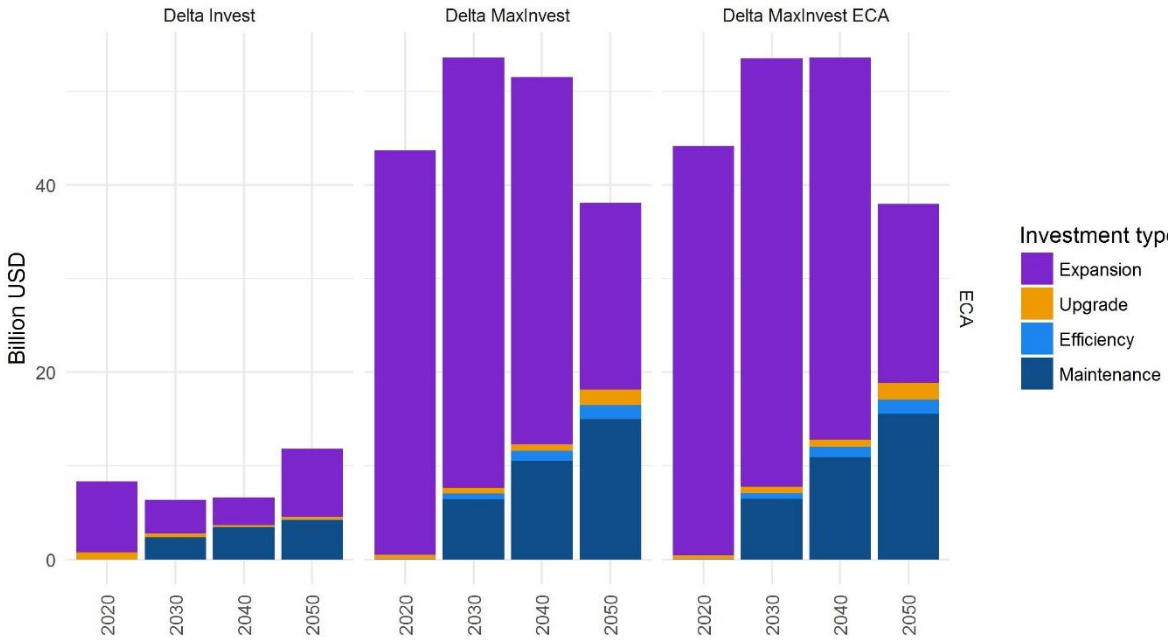

Figure SI 43. Summary of additional irrigation investment scenarios needed for the Europe and Central Asia region from 2020-2050 region compared to *ZeroInvest* ($ billion, 2000 US dollar)

3.4. Latin America and Caribbean

FAO estimates that 91 Mha of cropland could be irrigated in Latin America and Caribbean (LCR), while in 2010 only about 15 Mha were already irrigated (FAO, 2017). Without investment in infrastructure for irrigation, by 2050, the water price for irrigation increases and leads to a decrease in the irrigated area by 18% or 2.4 Mha. Under *Invest*, there would be 10 Mha more irrigated areas in 2050 than *ZeroInvest* (68% higher than 2010). Under both *MaxInvest* and Region *MaxInvest* an additional 41 Mha would be converted to irrigation by 2050 compared to *ZeroInvest*, which would be approx. 60% of the potential irrigable area defined by FAO. Rainfed areas are lower under all investment scenarios and total cropland is also 3-4% lower, sparing up to 5.4 Mha by 2050 from conversion to cropland in *MaxInvest* compared to *ZeroInvest* (Figure SI 44). Total crop production is about 24 Mt dm lower under *Invest*, compared to *ZeroInvest*, about 5.8 Mt dm higher in *MaxInvest*, and 47 Mt dm higher under the Region *MaxInvest*, producing more corn, sugar cane, wheat and rice and less soybean and cotton. Consumption and calorie availability increase compared to *ZeroInvest* due to the relatively lower crop prices under the investment scenarios. Water demand increases dramatically, but the relative increase in water efficiency under both *MaxInvest* scenarios compared to *ZeroInvest* and the decrease in cropland area and increase in crop production implies that the productivity of irrigated areas are significant. Deforestation and conversion of other natural land is higher under the *MaxInvest* and Region *MaxInvest* scenarios. GHG emissions from the AFOLU sector are slightly higher in *Invest* due to increased LUC and crop production, while under *MaxInvest* and Region *MaxInvest* the emissions are more than 25% higher coming almost entirely from increased deforestation and conversion of natural land for cropland and grassland. In *ZeroInvest*, depreciation costs are about $1.2 billion per year over 40 years (Figure SI 46). The modest expansion of irrigated area that takes place under *Invest* cost an additional $2 billion per year over 40 years. The massive expansion of irrigated areas which takes place under *MaxInvest* and Region *MaxInvest* costs an additional $7.9 billion per year.

The uncertainty of these results is in terms of irrigated area expansion under *Invest* is +9/-28% and +24/-103% for *MaxInvest*.

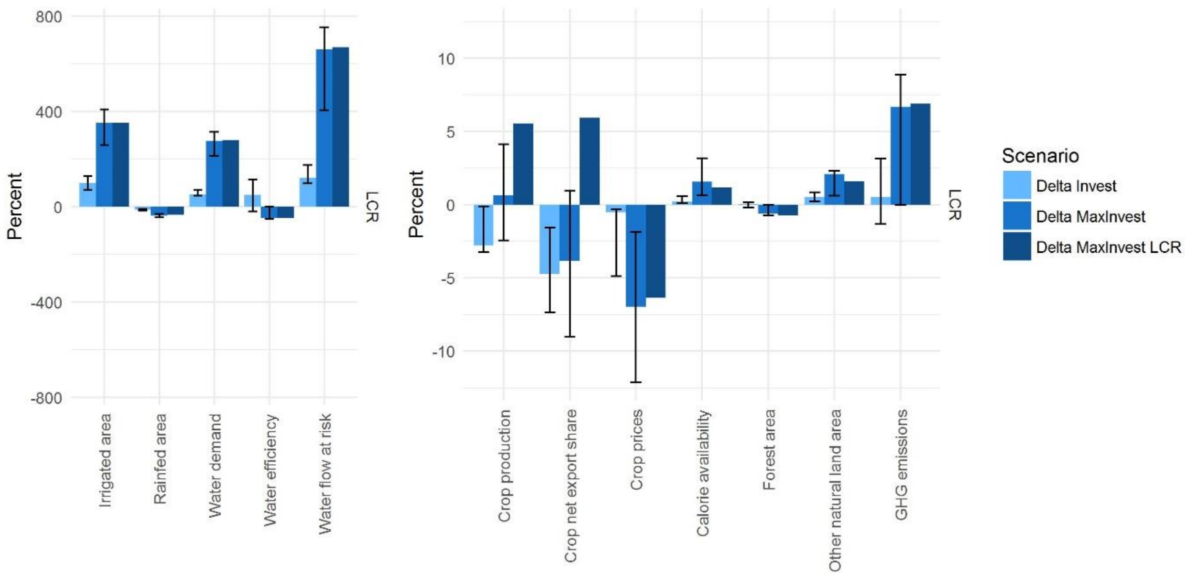

Figure SI 44. Summary of percent difference between investment scenarios and *ZeroInvest* in 2050 for various indicators in Latin America and Caribbean Region

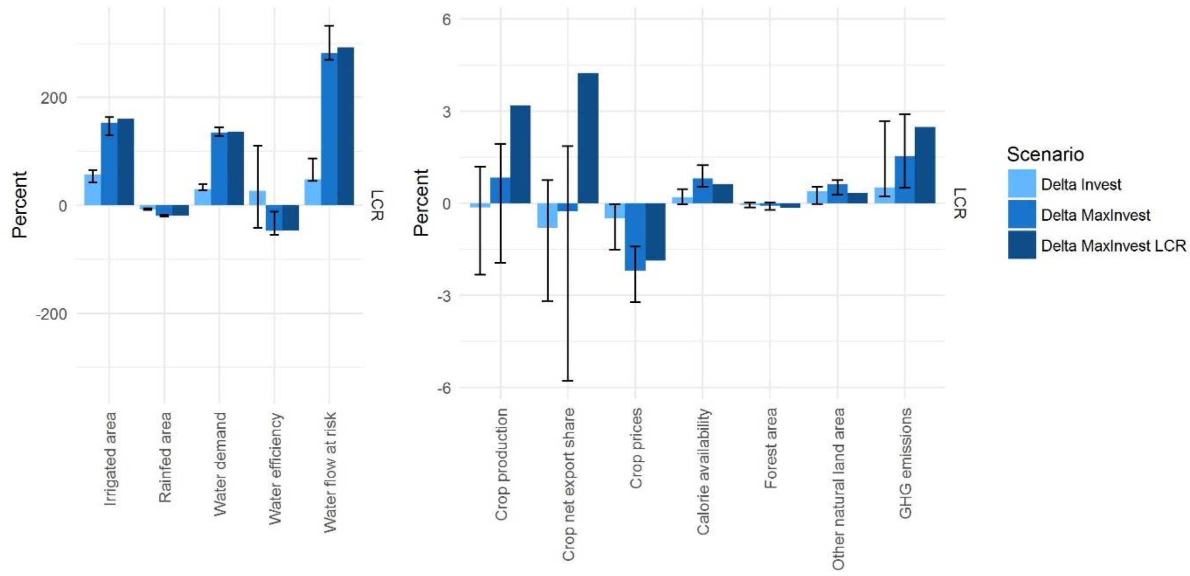

Figure SI 45. Summary of percent difference between investment scenarios and *ZeroInvest* in 2030 for various indicators for the Latin American and Caribbean region.

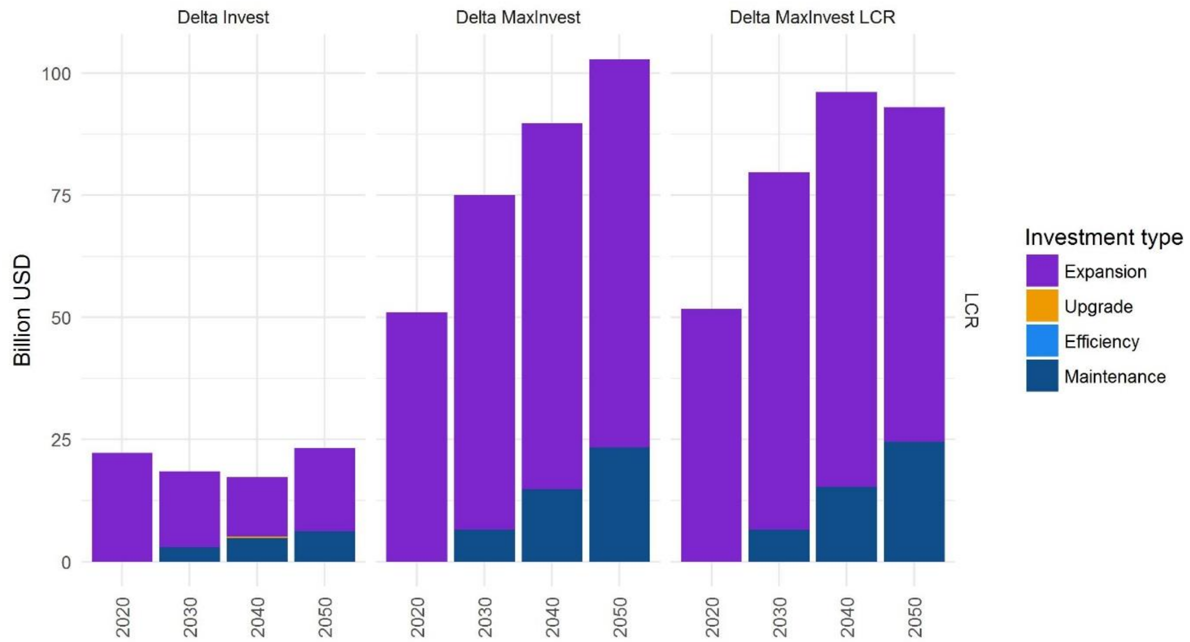

Figure SI 46. Summary of additional irrigation investment scenarios needed for the Latin American and Caribbean region from 2020-2050 region compared to *ZeroInvest* ($ billion, 2000 US dollar)

3.5. Middle East and North Africa

FAO estimates that 29 Mha of cropland could be irrigated in the Middle East and North Africa, in 2010 only 15 Mha were already under irrigation (FAO, 2017; Frenken, 2009). Under the ambitious irrigation strategies, (*MaxInvest* and Region *MaxInvest*), there is 6.5 Mha more irrigated area in 2050 compared to *ZeroInvest* which sees a decrease in irrigated area of 1.4 Mha (Figure SI 47). The expansion in irrigated area in *MaxInvest* would which would correspond to about 66% of the potentially irrigable land according to the FAO (Frenken, 2009). Crop production is higher under the investment scenarios by 22 to 29 Mt dm producing more sugar cane, rice, wheat, sorghum, and cotton. Total cropland is 1 Mha higher under *Invest* and *MaxInvest* compared to *ZeroInvest* by 2050, which implies a significant increase in intensification from irrigation which can be seen by the increase average crop yield under the investment scenarios. Crop consumption and calorie availability increase slightly due to the reduced crop prices under the investment scenarios. Despite the increase in production, the region is still a net importer but the share of total domestic consumption coming from imports decreases from 56% of the total domestic consumption in 2050 under *ZeroInvest* to only 40% of the domestic consumption under Region *MaxInvest*. Demand for water increases by more than 25% under the investment scenarios, although the region produces more product per unit water (+32%-45% more) because the expansion of irrigation is in more efficient irrigation systems such as drip and sprinkler systems. Under different investment scenarios, AFOLU GHG emissions are about 4% higher than *ZeroInvest* in 2050. Depreciation costs for irrigation systems in MNA are about $1.4 billion per year over 40 years under *ZeroInvest*. For the expansion and upgrade costs under the *Invest* scenario an additional $1 billion per year over 40 years is needed and $1.6 billion per year for *MaxInvest* and Region *MaxInvest* (Figure SI 49).

The uncertainty of these results is in terms of irrigated area expansion under *Invest* is +8/-19% and +6/-15% for *MaxInvest*.

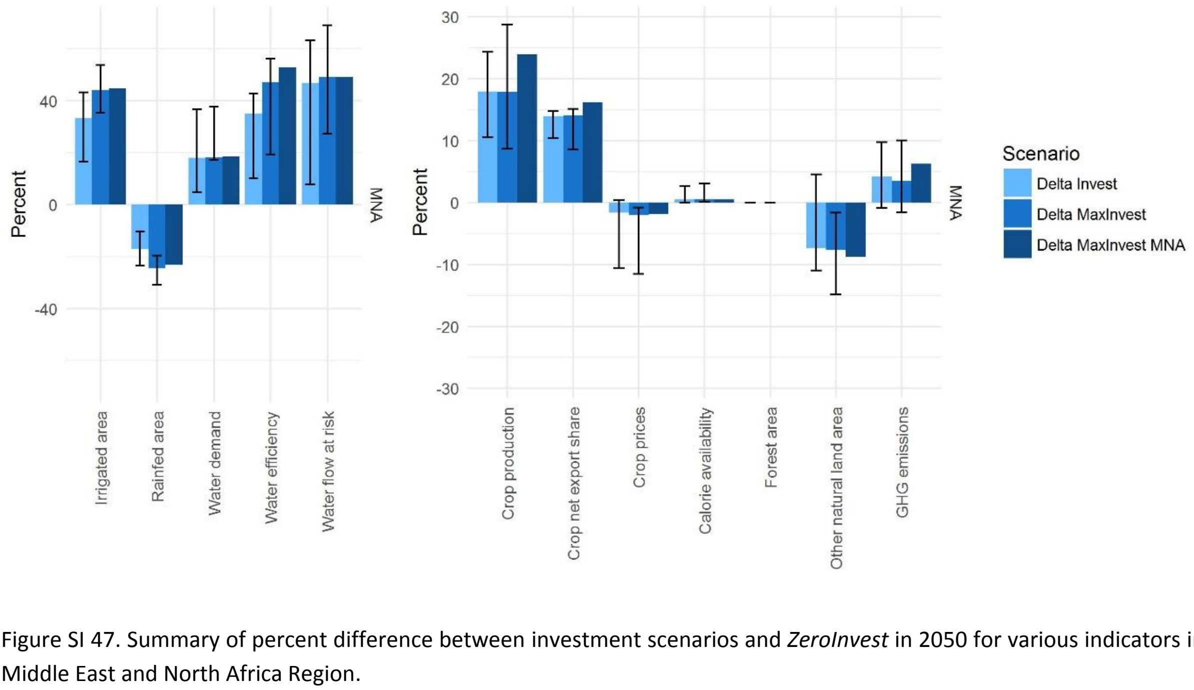

Figure SI 47. Summary of percent difference between investment scenarios and *ZeroInvest* in 2050 for various indicators in Middle East and North Africa Region.

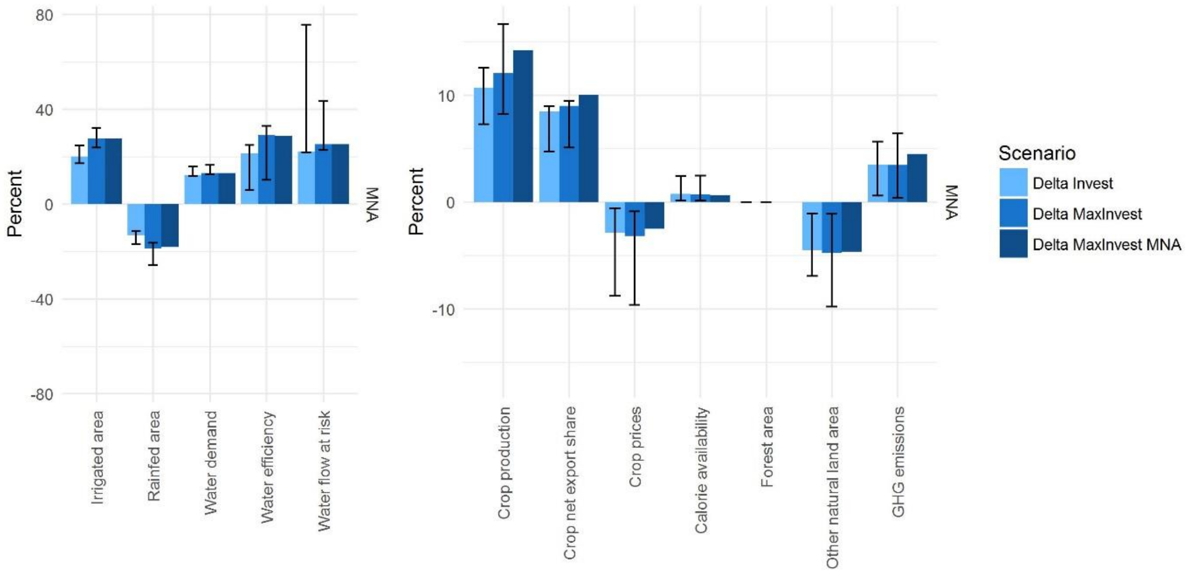

Figure SI 48. Summary of percent difference between investment scenarios and *ZeroInvest* in 2030 for various indicators in the Middle East and North Africa Region.

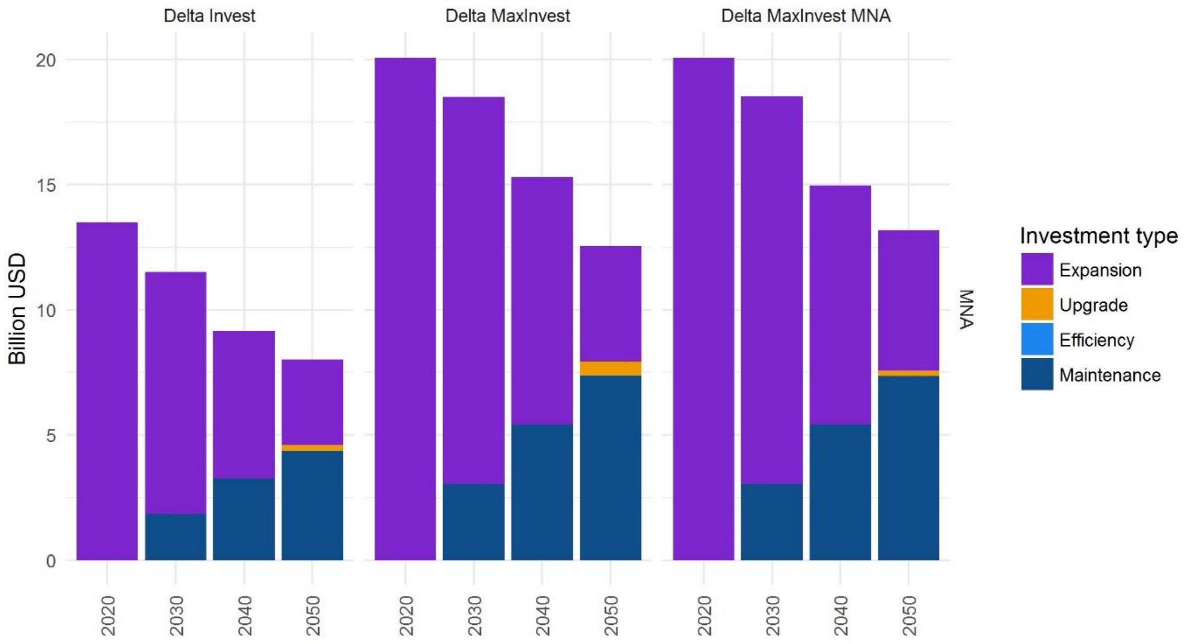

Figure SI 49. Summary of additional irrigation investment scenarios needed for the Middle East and North Africa region from 2020-2050 region compared to *ZeroInvest* ($ billion, 2000 US dollar)

3.6.South Asia

FAO estimates that 170 Mha of cropland could be irrigated in the South Asia and in 2010 about 88 Mha were already under irrigation (FAO, 2017; Frenken, 2011). With investment in irrigation infrastructure, irrigated area in South Asia would decline by 11 Mha (-11%) from 2010 to 2050. Under *Invest* in 2050, there would be 38 Mha more irrigated area than under *ZeroInvest* (36% higher than 2010 levels) and 50 Mha more under *MaxInvest* and Region *MaxInvest*, corresponding to about 77% of the potentially irrigable land as defined by FAO (Frenken, 2011). 35-44 Mha less rainfed area would be needed under the investment scenarios in 2050 compared to *ZeroInvest*, however net cropland area is still about 2 to 3% higher in 2050 (3.2 to 5.6 Mha more than *ZeroInvest* in 2050) (Figure SI 50). Production is about 40 to 50 Mt dm higher in the investment scenarios (and also marginally higher Region *MaxInvest* scenarios for other the regions) when compared to *ZeroInvest* in 2050. Consumption is also about 2.5% higher under the investment scenarios and calorie availability increases (51-71 kcal per capita per day more relative to *ZeroInvest*) due to the lower crop prices. In 2050 under *ZeroInvest*, the region is a net importer, but the region imports less under the investment scenarios. Water demand increases, while the efficiency in terms of crop produced per cubic meter of water is higher only under the *MaxInvest* and Region *MaxInvest*. Between 2.2 and 3.1 Mha of natural land are spared from conversion to grassland and cropland under the *Invest* and *MaxInvest* scenarios compared to *ZeroInvest*. Under different investment scenarios, AFOLU GHG emissions are about 6% higher than *ZeroInvest* in 2050. Without investment, depreciation costs for irrigation systems would be $1.9 billion per year over 40 years. An additional $3.4 billion per year over 40 years is required in the *Invest* scenario due to the expansion of irrigated areas. Under *MaxInvest*, an additional $4.8 billion per year is needed compared to *ZeroInvest* (Figure SI 52).

The uncertainty of these results is in terms of irrigated area expansion under *Invest* is +2/-15% and +4/-12% for *MaxInvest*.

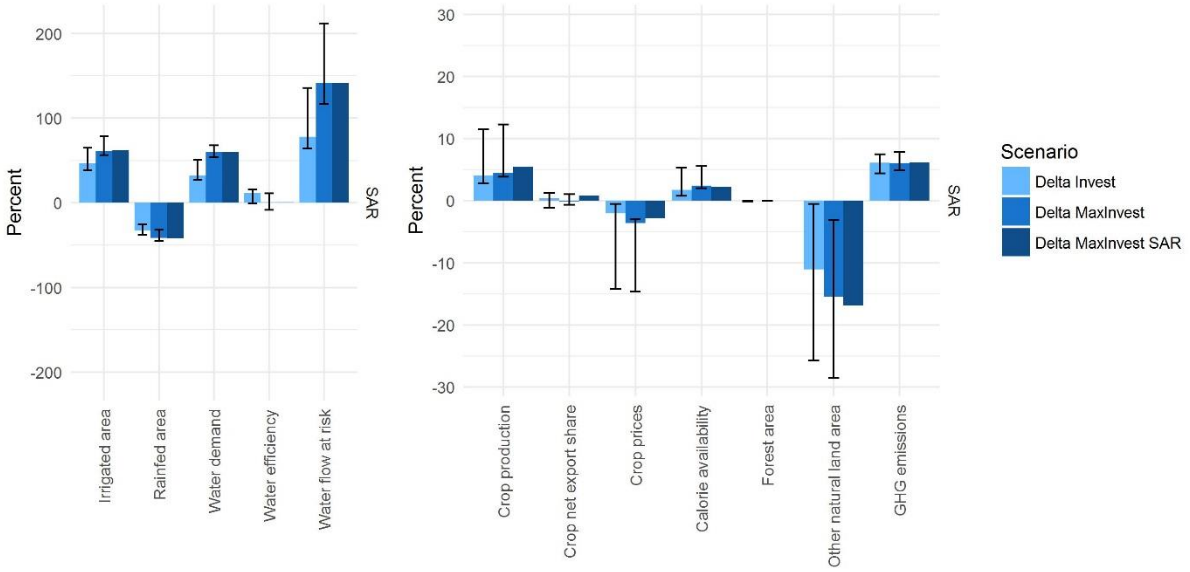

Figure SI 50. Summary of percent difference between investment scenarios and *ZeroInvest* in 2050 for various indicators in South Asia Region

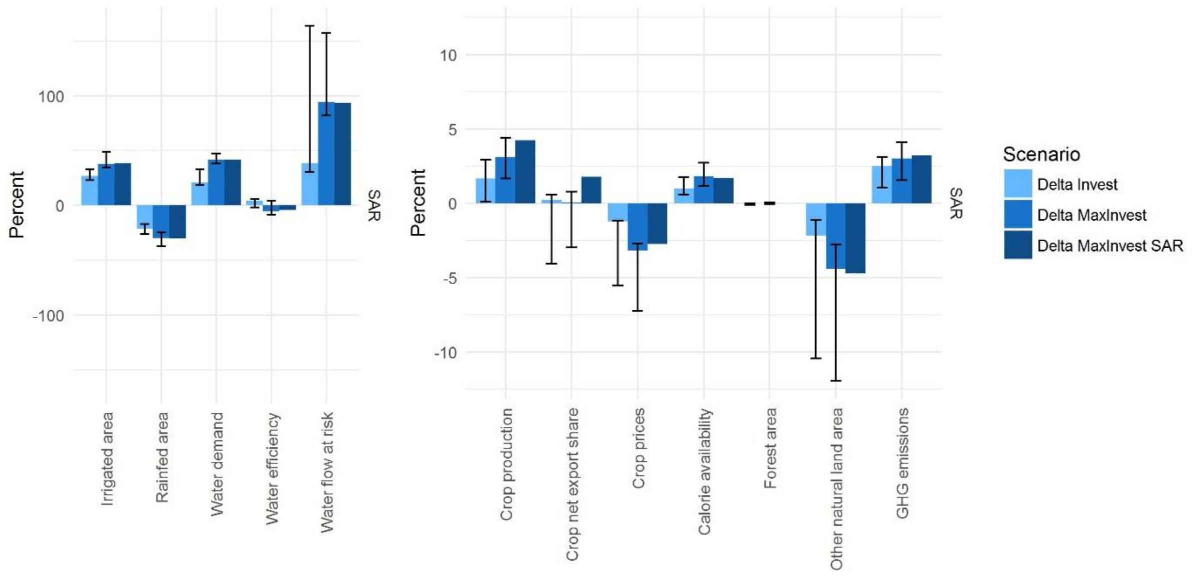

Figure SI 51. Summary of percent difference between investment scenarios and *ZeroInvest* in 2030 for various indicators in the South Asia Region.

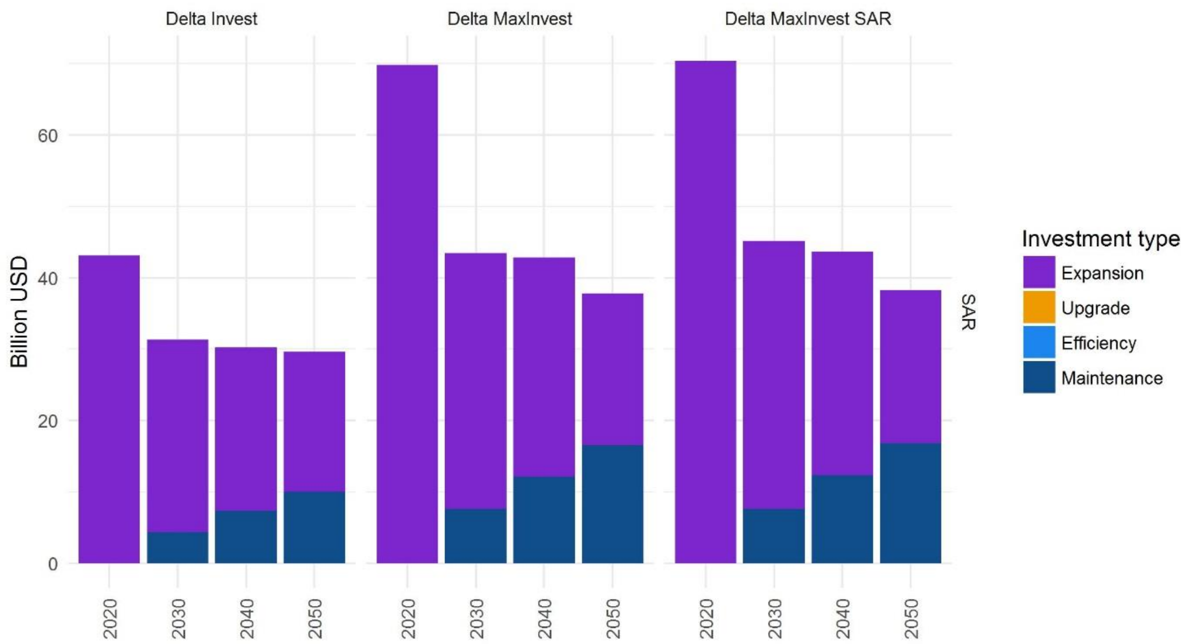

Figure SI 52. Summary of irrigation costs under investment scenarios for South Asia region ($ billion, 2000 US dollar)

4. Extreme scenarios

To evaluate the uncertainty of the impacts of irrigation investment strategies within our modeling framework, we conducted a sensitivity analysis. After testing the modeling assumptions individually, we combine different parameters and assumptions from the sensitivity scenarios to create extreme scenarios (Table SI 2). 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 *CombinedHigh* scenario relies on the socioeconomic narrative SSP2, climate scenario RCP8p5 modeled with MIROC, and the high water efficiency assumption (WaterEff_High). This combination of uncertainties was selected because the other scenarios led to smaller impacts on the investment costs. *CombinedHigh2* is the *CombinedHigh* scenario with open trade assumptions.

Table SI 2. Overview of the model assumptions used in the extreme scenarios

	socioeconomic pathway	**dietary pattern**	**climate change impact**	**water application efficiency**	**trade openness**
Combined High	SSP2	SSP2 diet	RCP8p5 MIROC	high WAE	Normal trade
Combined High2	SSP2	SSP2 diet	RCP8p5 MIROC	high WAE	Open trade
Combined Low	SSP1	Healthy and Sustainable	RCP2.6 IPSL	high WAE	Normal trade
Combined Low2	SSP1	Healthy and Sustainable	RCP2.6 IPSL	high WAE	Restricted trade

The *Combined_Low* scenario relies on the socioeconomic narrative of SSP1 and the Healthy & Sustainable Diet scenario. This scenario combination is internally consistent because one of the features of SSP1 are sustainable diets and the Healthy & Sustainable Diet scenario represents an even more sustainable diet than the default one of SSP1. These two dimensions will be combined with the RCP2p6 climate scenario modeled by IPSL. This again represents a consistent combination as RCP2p6 is a low climate change scenario compatible with the sustainability narrative of SSP1. *CombinedLow2* is the *CombinedLow* scenario with restricted trade assumptions.

For the cumulative investment costs in the developing regions by 2050, the *CombinedHigh2*, *CombinedHigh*, *CombinedHigh2_MaxInvest* and *CombinedHigh_MaxInvest* scenarios have the largest investment costs in all regions except MNA when compared to the *Invest* and *MaxInvest* scenarios respectively. The *CombineHigh_MaxInvest* is about $140 billion more expensive than *WatEff_High MaxInvest* scenario.

By 2050, irrigated area is highest in all of the regions except SAR, MNA, AFR for *CombinedHigh2 MaxInvest*. For SAR, the *CombinedHigh MaxInvest* has the higher irrigated area (+2 Mha compared to *CombinedHigh2*).

Of all the scenarios food security (kcal/cap/day) is highest for SAR and AFR in the *CombinedLow2_MaxInvest* scenario. Compared to the *MaxInvest SSP1* scenario, food security is 1.2% higher in SAR, and 0.8% higher in LCR, ECA and EAP. In AFR, food security is 0.2% higher.

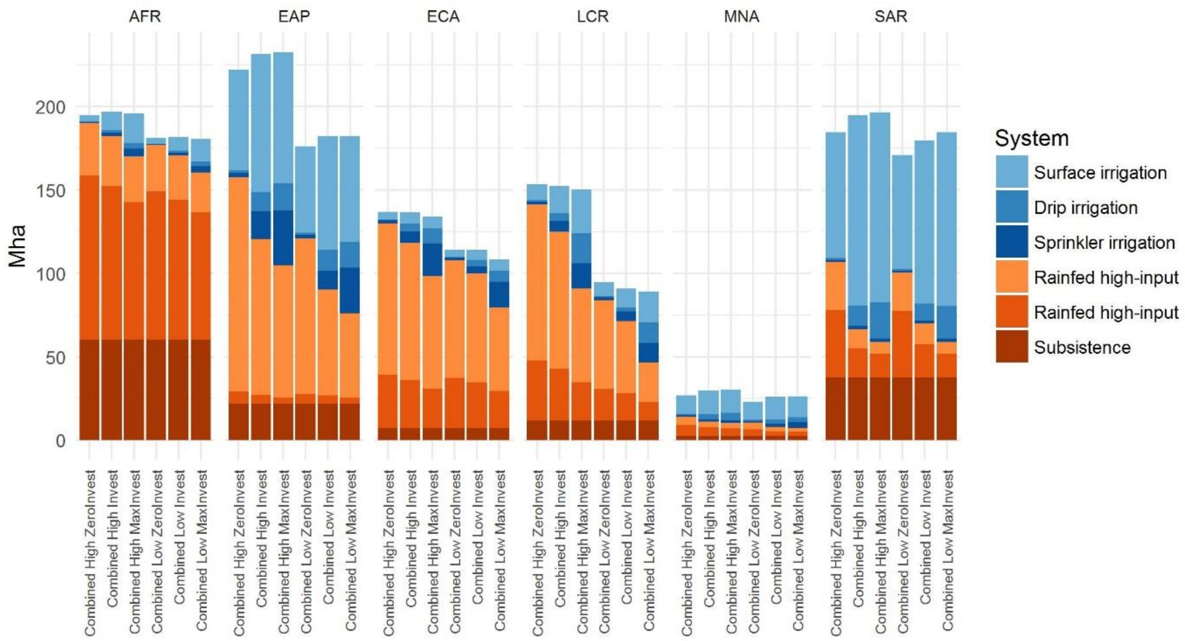

Figure SI 53. Cropland area by system under different combinations of uncertainty parameters under *ZeroInvest*, *Invest*, and *MaxInvest* by region in 2050 (Mha)

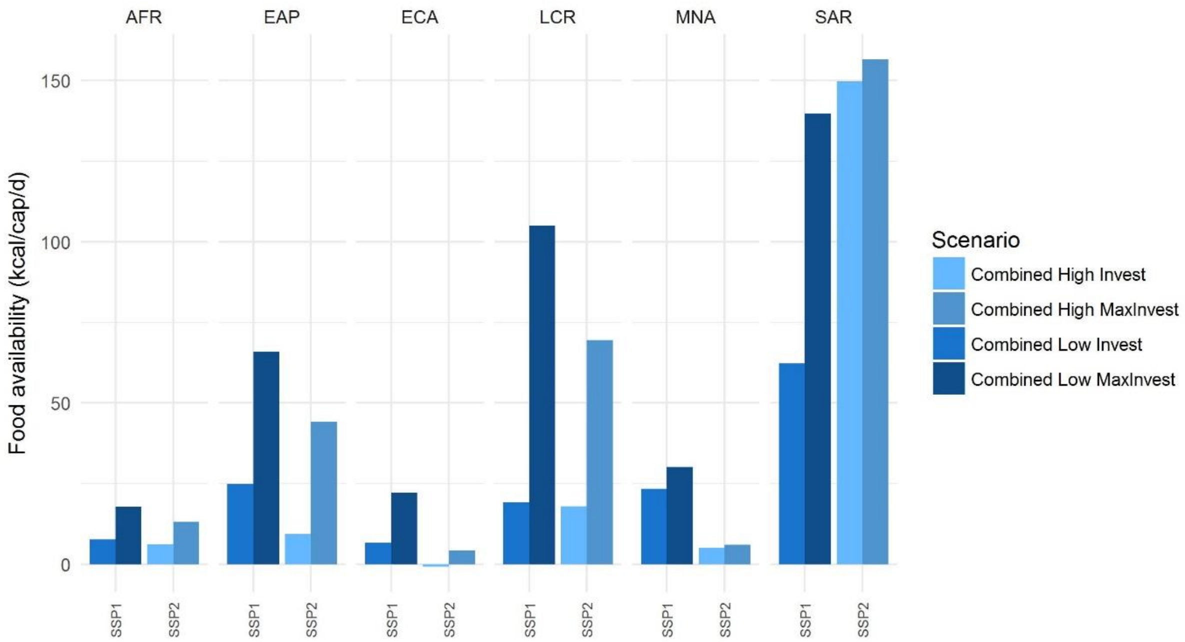

Figure SI 54. Change in food availability under different combinations of uncertainty parameters compared to *ZeroInvest* in 2050 (kilocalorie per capita per day)

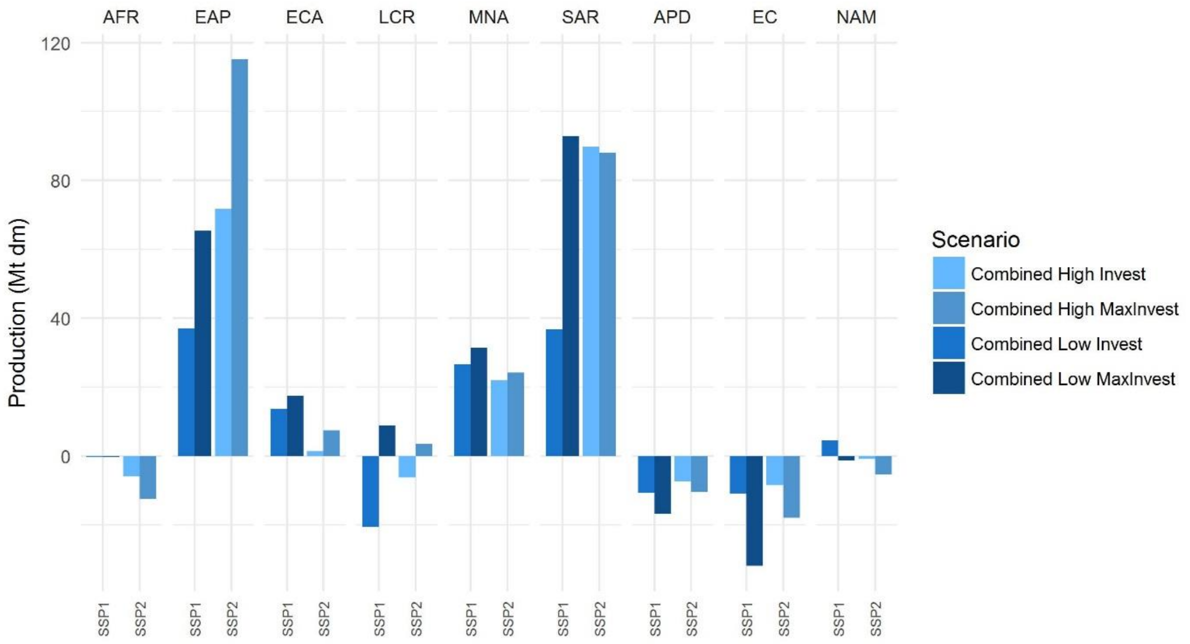

Figure SI 55. Change in crop production under different combinations of uncertainty parameters compared to *ZeroInvest* in 2050 by region (Mt dm)

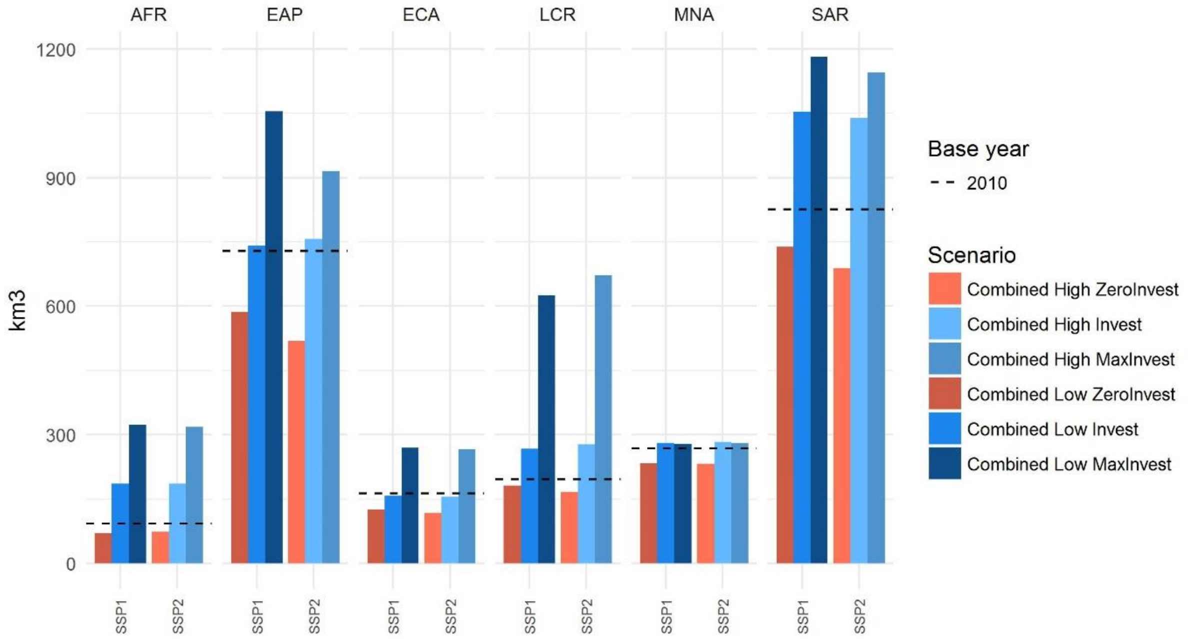

Figure SI 56. Water withdrawal for irrigation under different combinations of uncertainty parameters in 2050 by region (km^3)

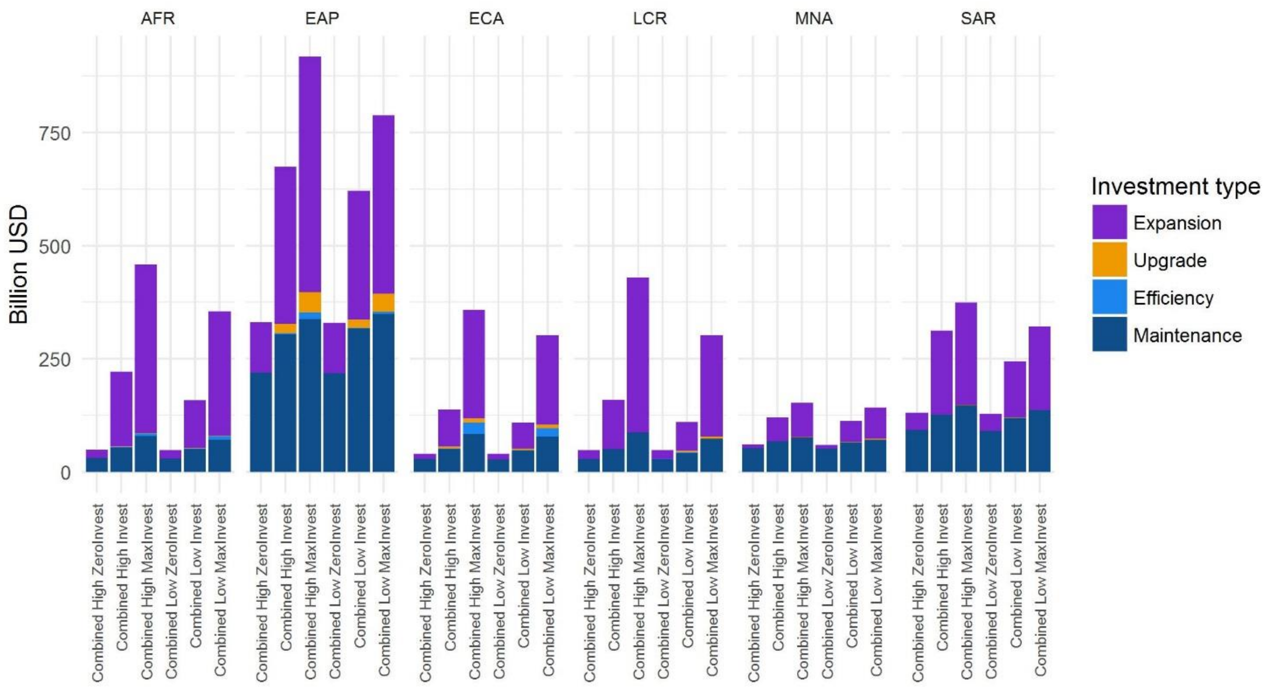

Figure SI 57. Cumulative developing country investment costs under different combinations of uncertainty parameters in 2050 by region ($ billion, 2000 US dollar)

5. Supplemental figures for 2030

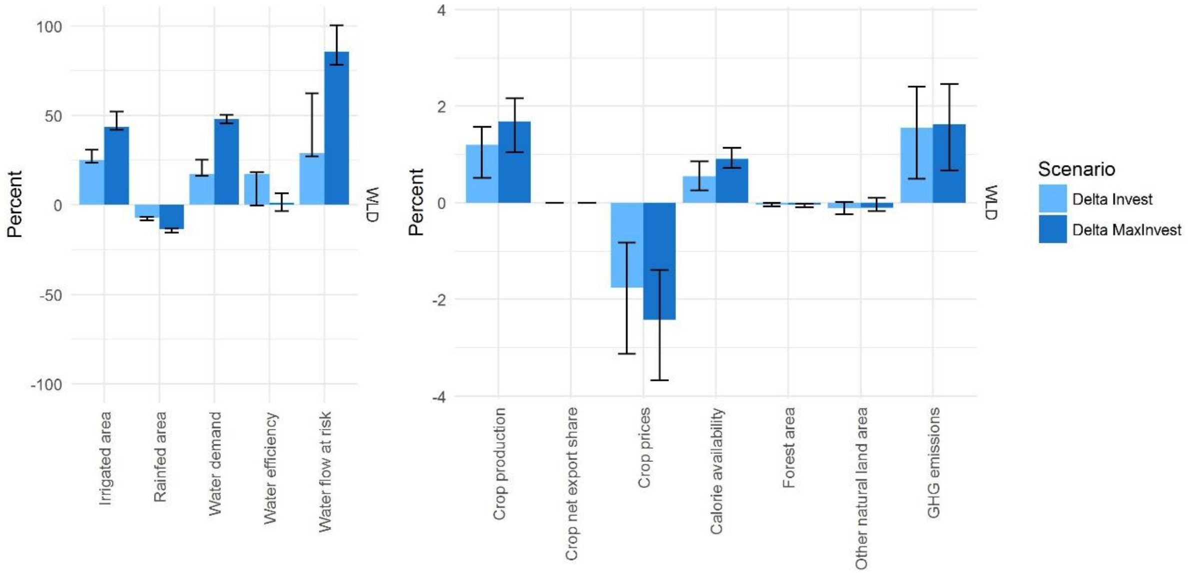

Figure SI 58. Summary of percent difference between investment scenarios and *ZeroInvest* in 2030 for various indicators at the Global level.

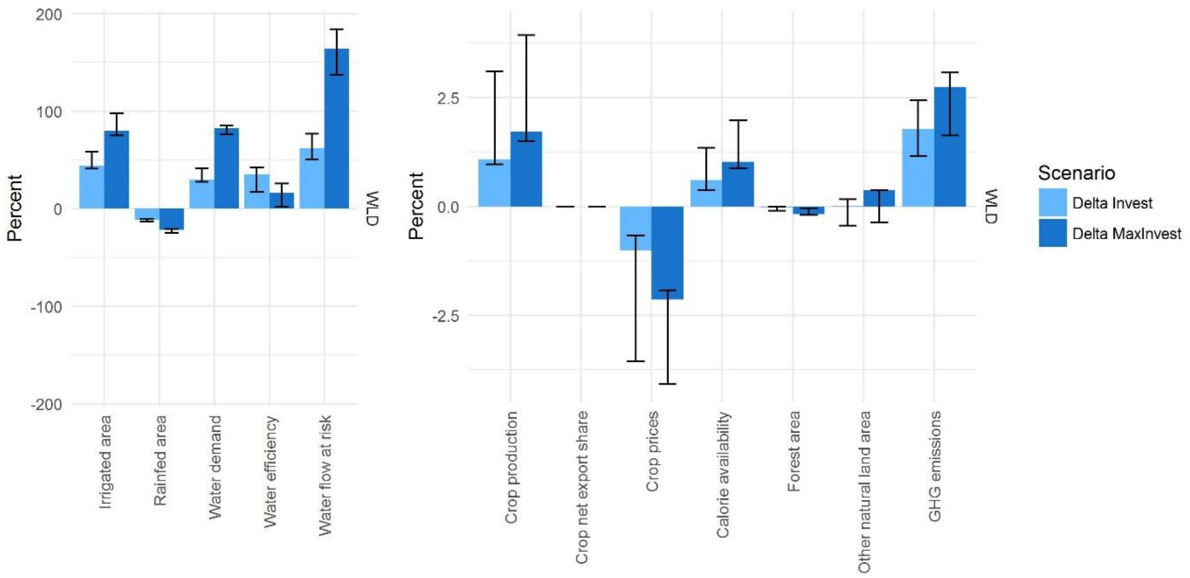

Figure SI 59. Summary of percent difference between investment scenarios and *ZeroInvest* in 2050 for various indicators at the Global level.

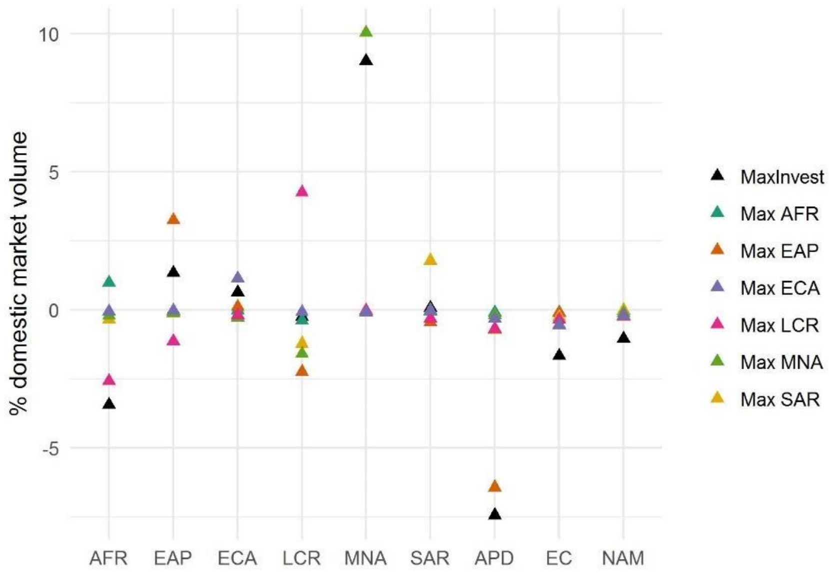

Figure SI 60. Difference in trade as a share of the domestic market volume compared to *ZeroInvest* in 2030 (%)

Figure SI 61. Net trade as a share of the domestic market for cereals in 2030 (%)

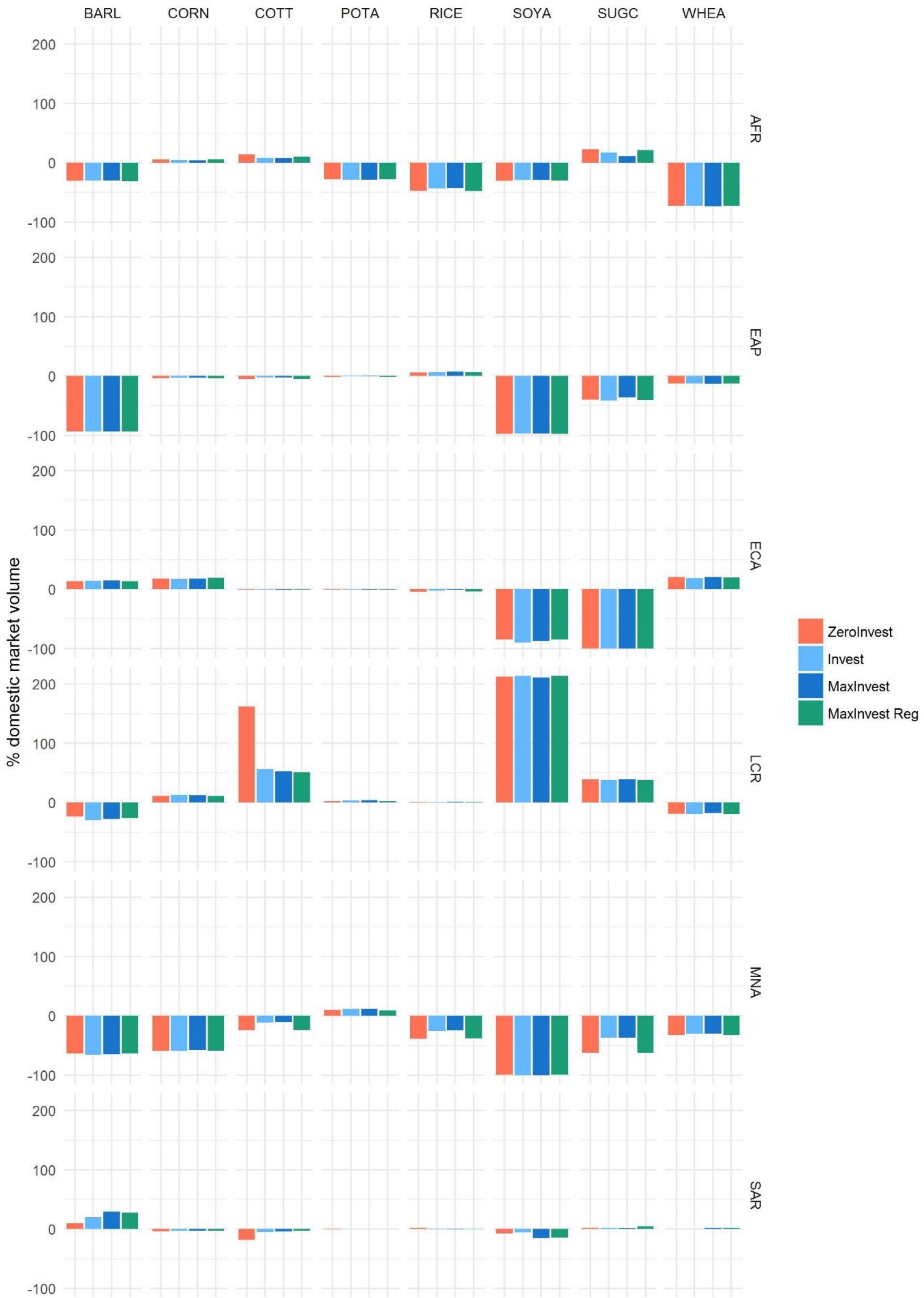

Figure SI 62. Net trade as a share of domestic consumption by crop in 2030 under *Invest*, *MaxInvest*, *ZeroInvest*, and the regional *MaxInvest* scenario (%)

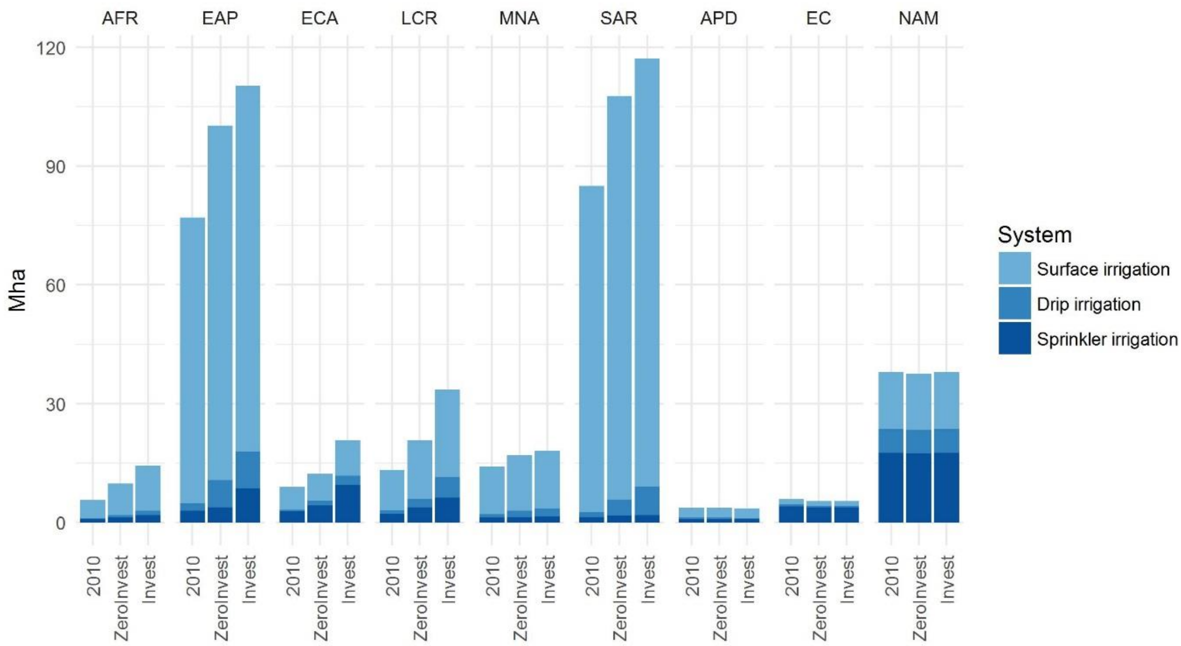

Figure SI 63. Irrigated area by system and region in 2010 and 2030 under *ZeroInvest*, *Invest*, and *MaxInvest* (Mha)

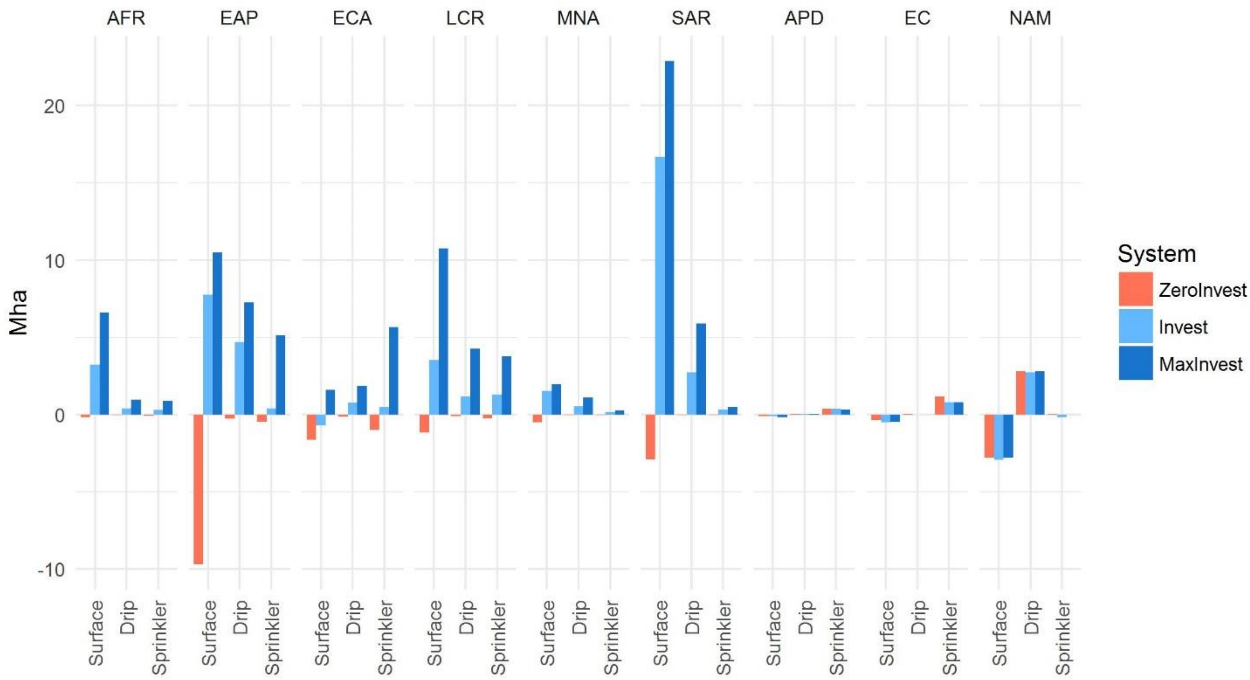

Figure SI 64. Net expansion of areas by system from 2010 to 2030 (net expansion excludes existing areas that are upgraded to more efficient systems or land retired/reverted to rainfed)

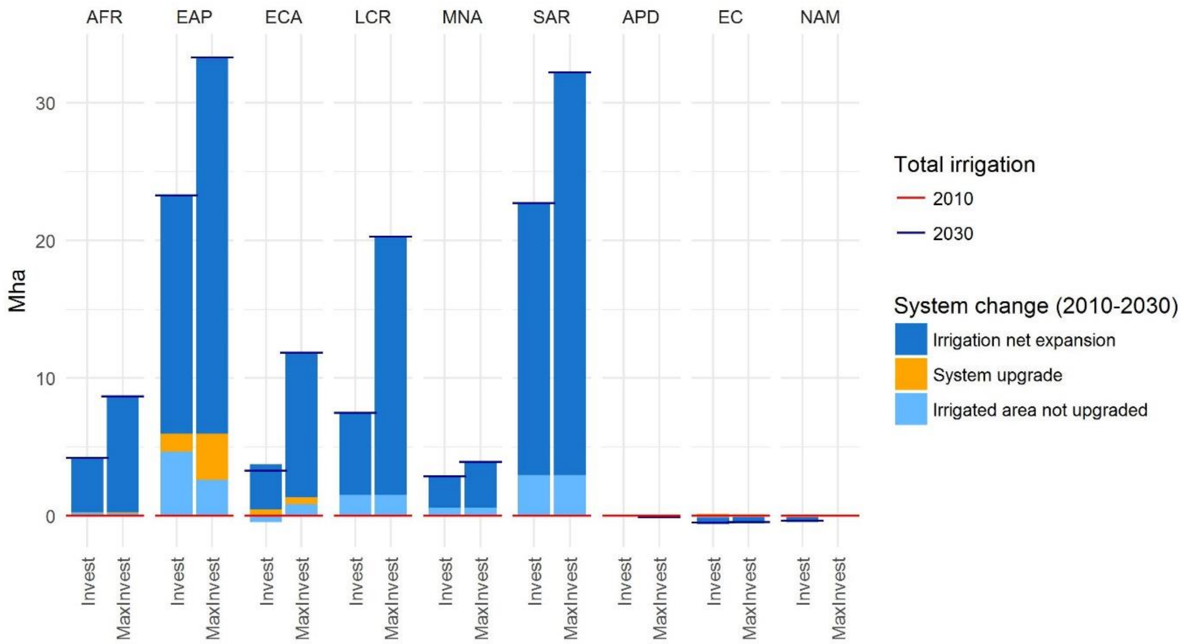

Figure SI 65. Cumulative irrigated area expansion and upgrade in *MaxInvest* and *Invest* from 2010 to 2030 (Mha)

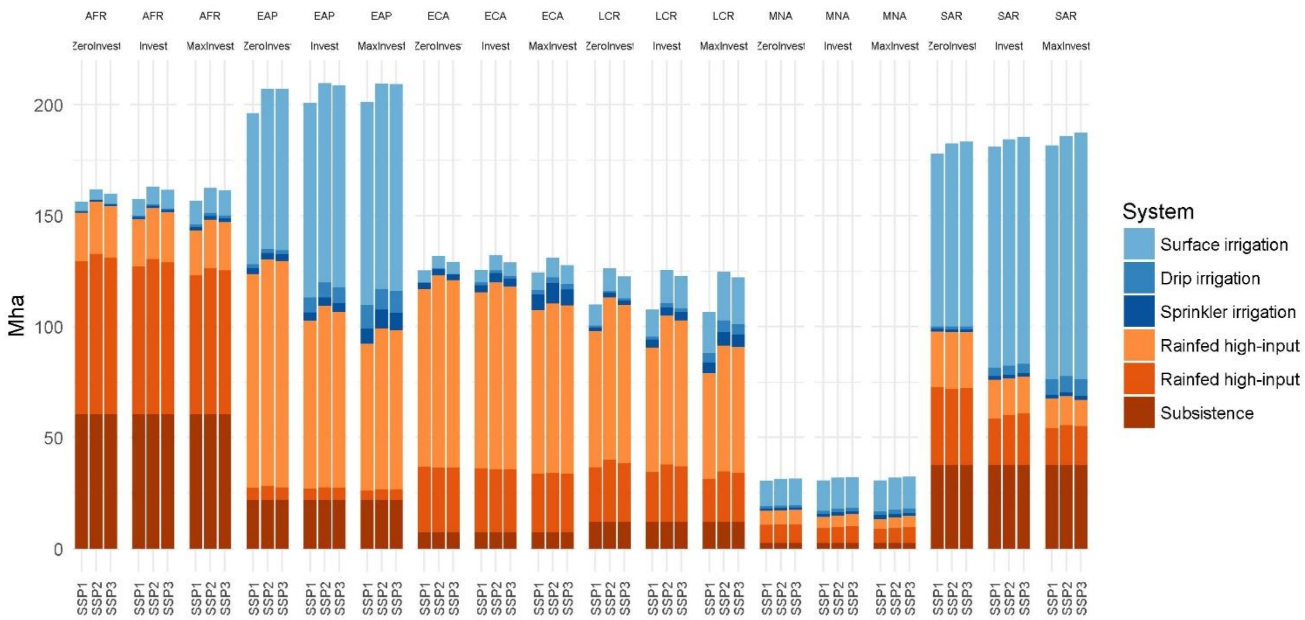

Figure SI 66. Cropland area by system under different socioeconomic conditions under *ZeroInvest*, *Invest*, and *MaxInvest* by region in 2030 (Mha)

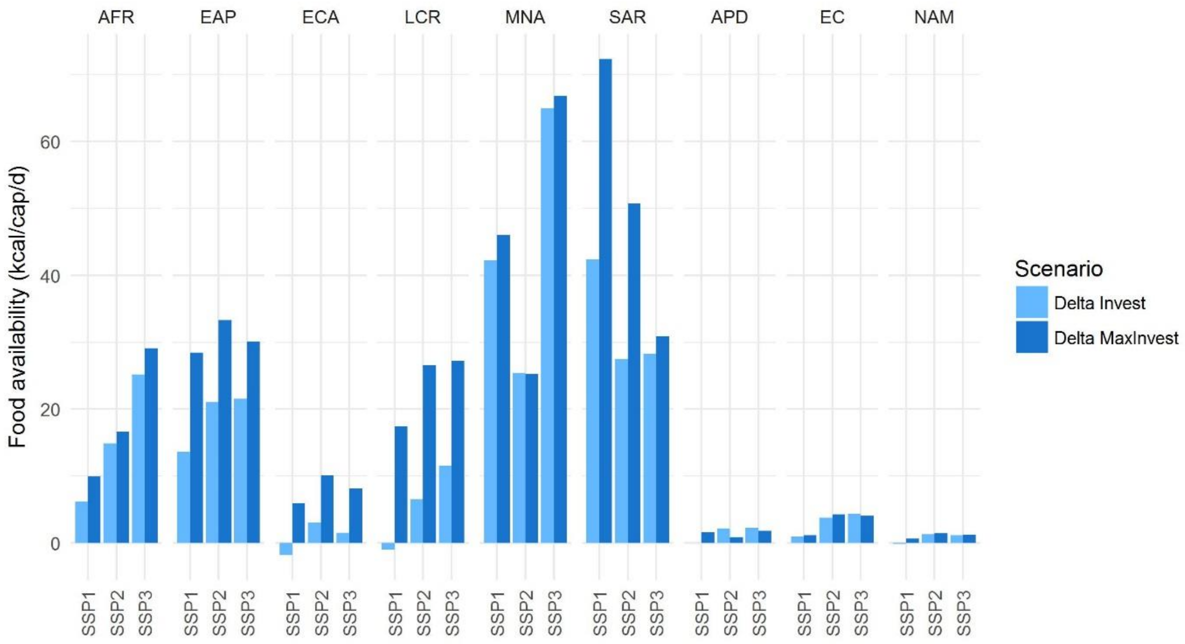

Figure SI 67. Change in food availability under different socioeconomic conditions compared to *ZeroInvest* in 2030 by region (kilocalorie per capita per day)

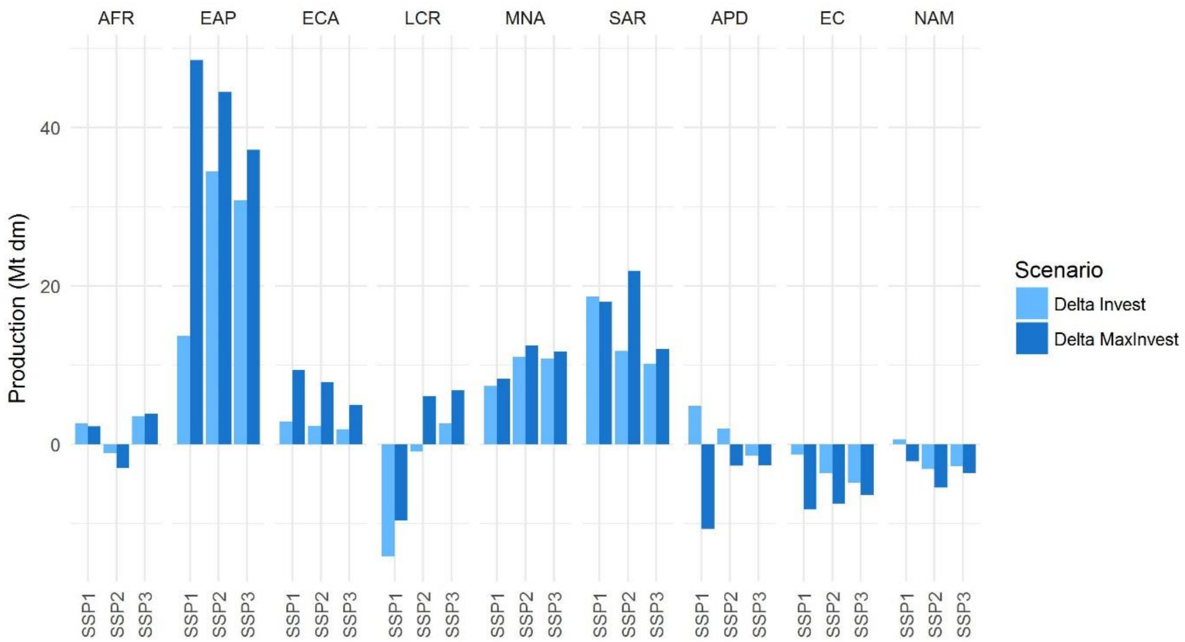

Figure SI 68. Change in crop production under different socioeconomic conditions compared to *ZeroInvest* in 2030 by region (Mt dm)

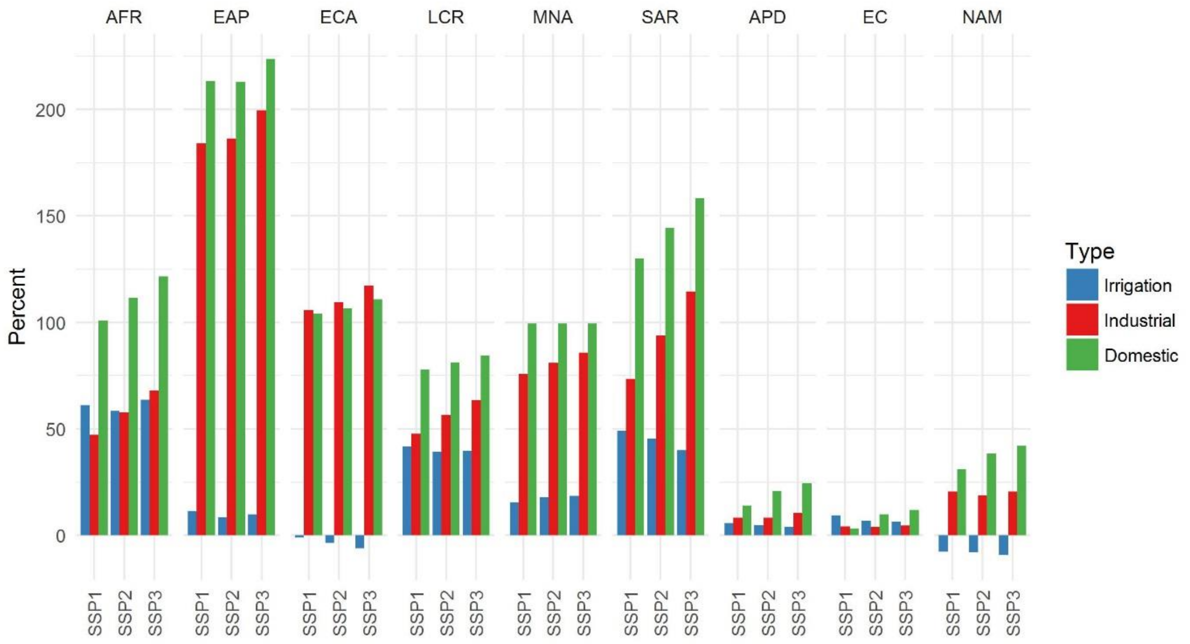

Figure SI 69. Relative differences in water demand in 2030 by sector under *MaxInvest* compared to 2010 levels of water demand under different socioeconomic conditions (%)

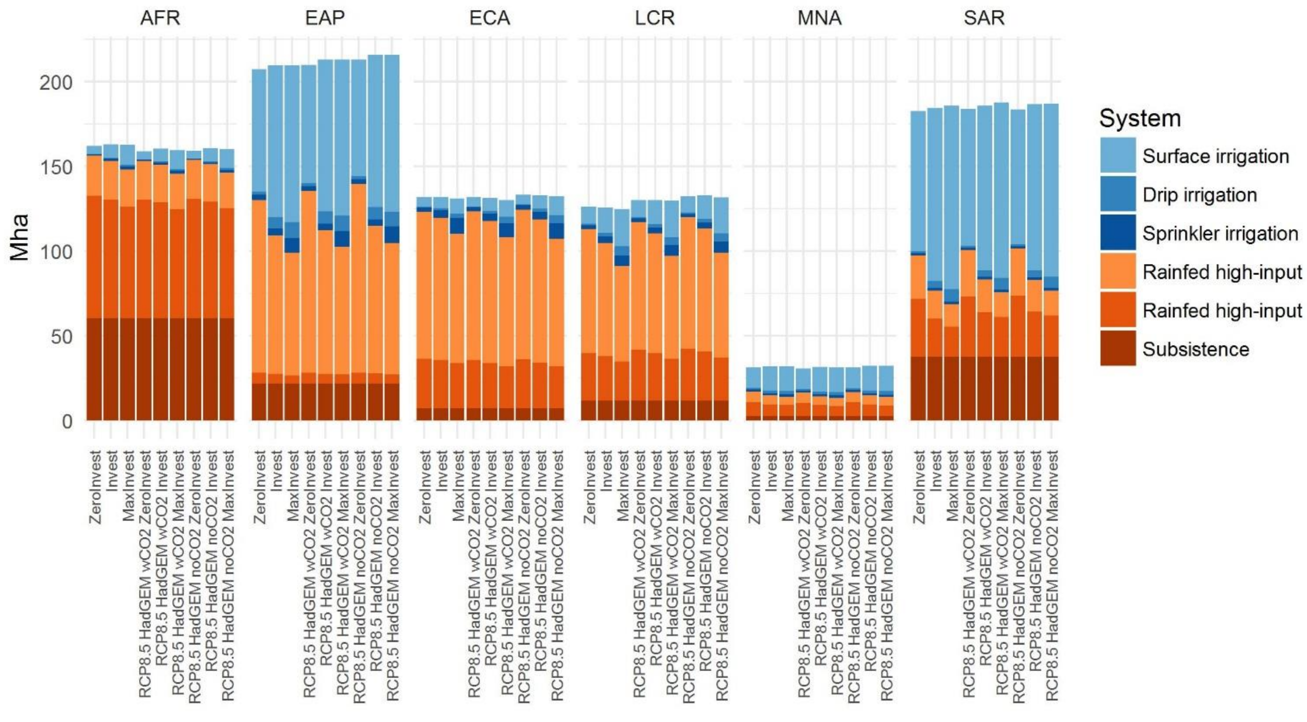

Figure SI 70. Cropland area by system under different climate futures under *ZeroInvest*, *Invest*, and *MaxInvest* by region in 2030 (Mha)

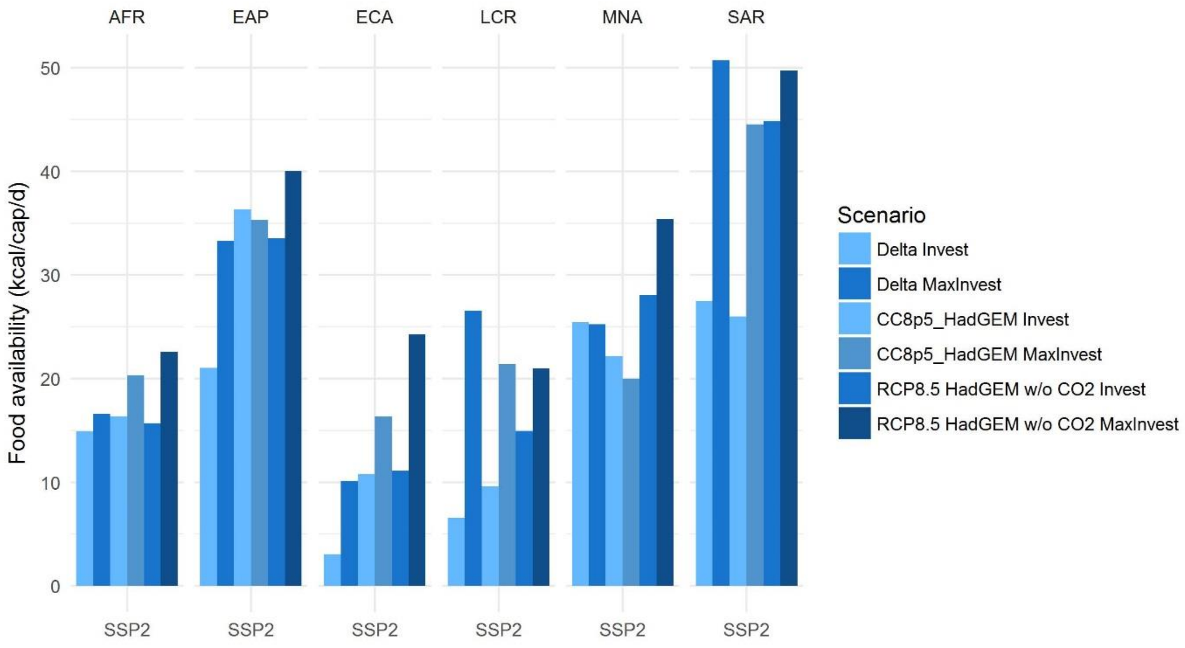

Figure SI 71. Change in food availability (kcal/cap/day) under different future climates compared to *ZeroInvest* in 2030 by region

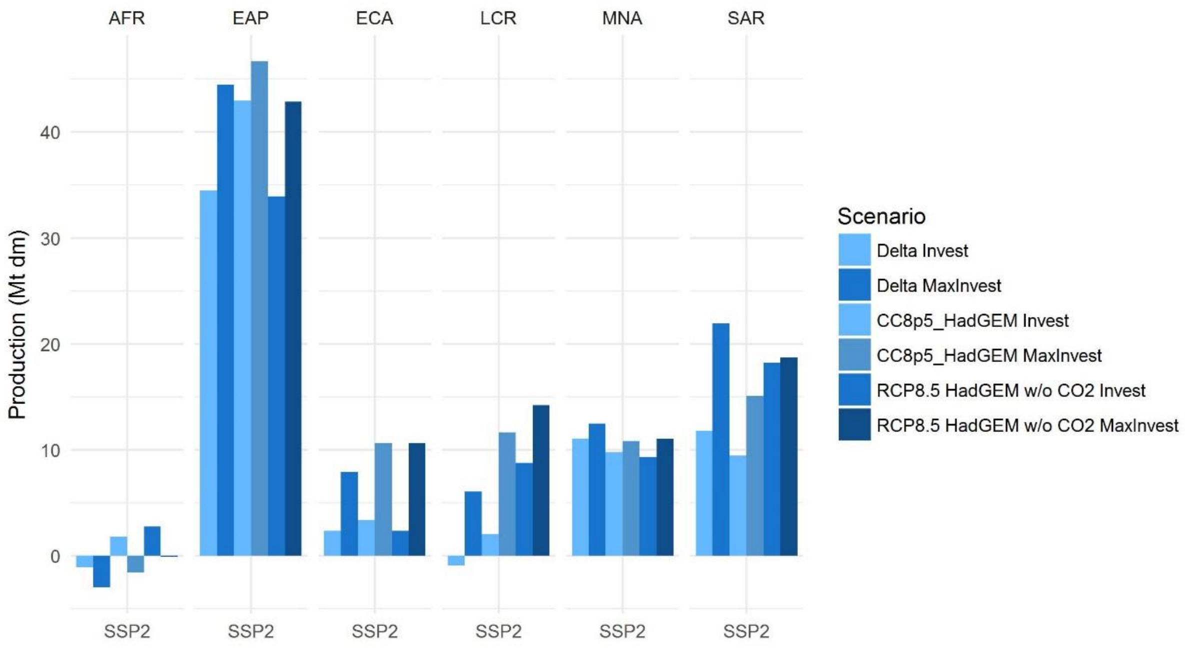

Figure SI 72. Change in production under different future climates compared to *ZeroInvest* in 2030 by region (Mt dm)

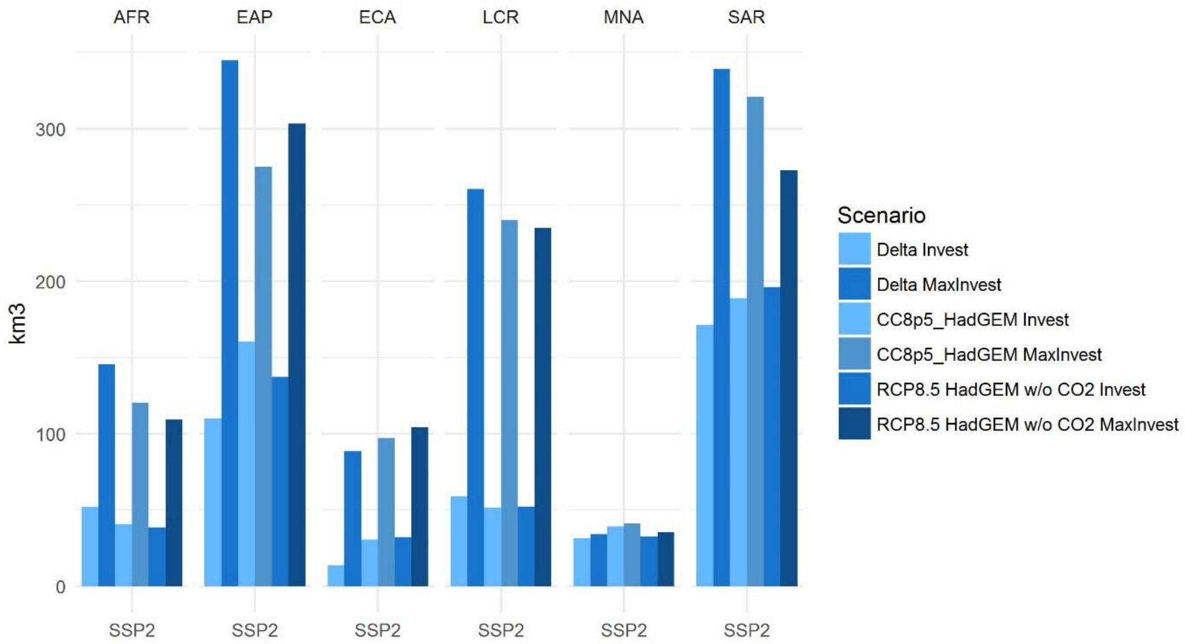

Figure SI 73. Water withdrawal for irrigation under different future climates in 2030 by region (km3)

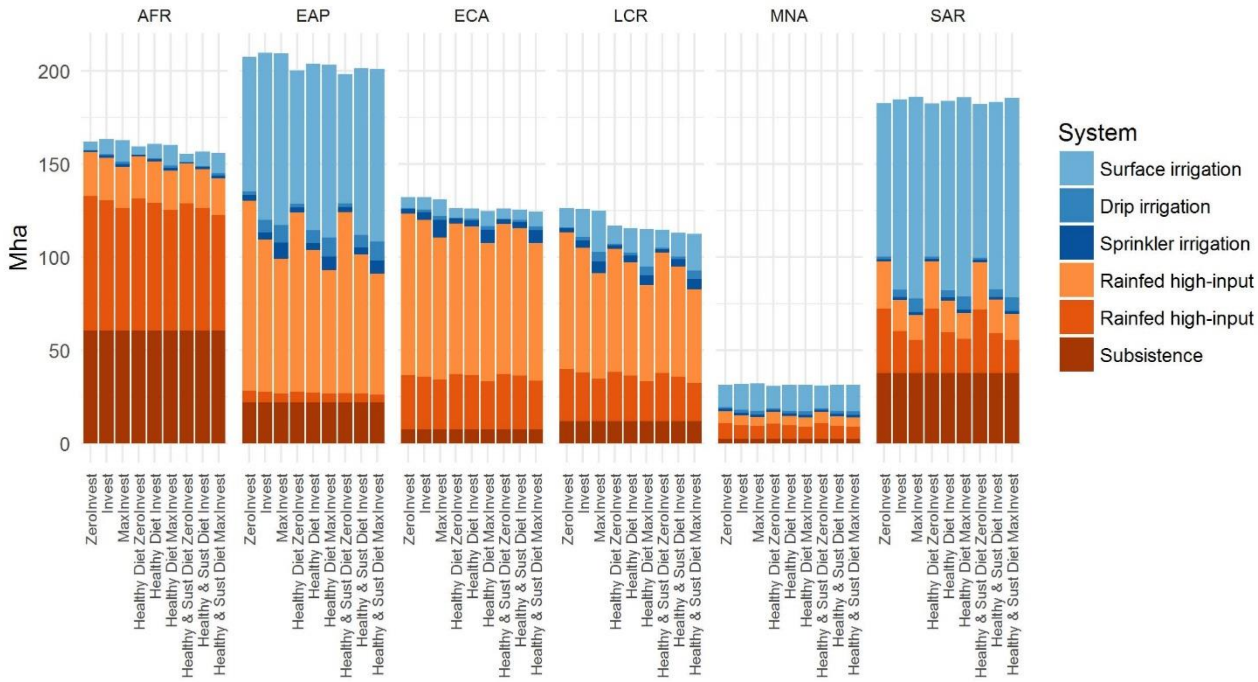

Figure SI 74. Cropland area by system under different dietary patterns under *ZeroInvest*, *Invest*, and *MaxInvest* by region in 2030 (Mha)

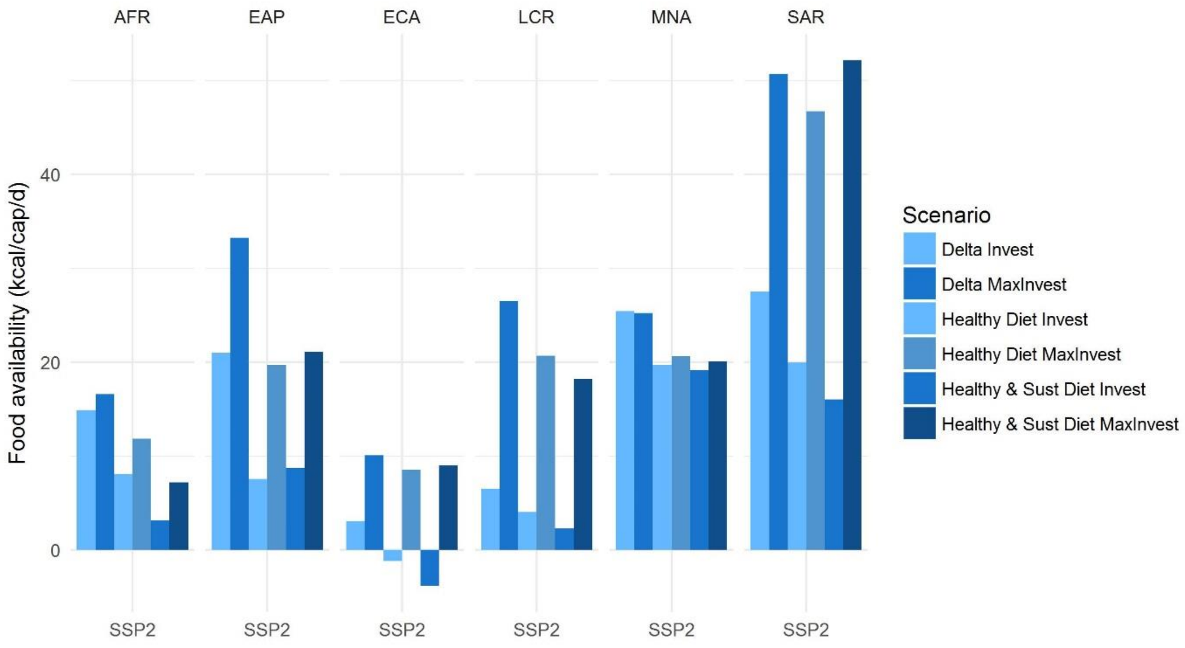

Figure SI 75. Change in calorie availability per capita per day under different dietary patterns difference from *ZeroInvest* in 2030 by region (kcal/cap/day)

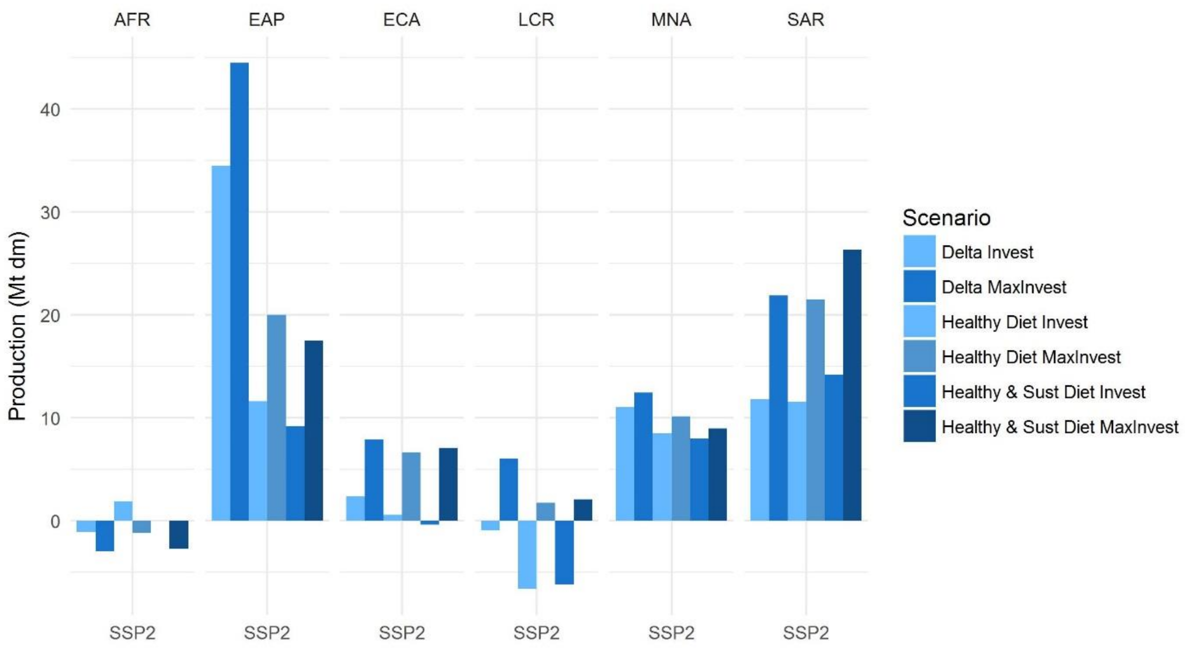

Figure SI 76. Change in crop production under dietary patterns compared to *ZeroInvest* in 2030 by region (Mt dm)

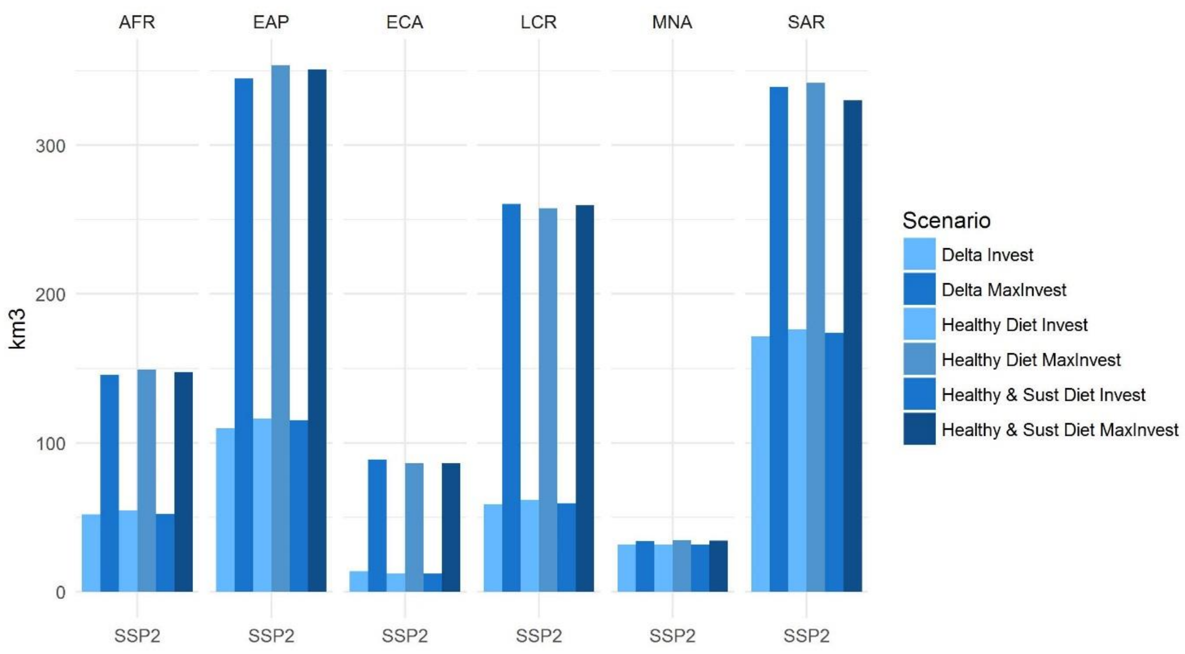

Figure SI 77. Change in water demand under dietary patterns compared to *ZeroInvest* in 2030 by region (km3)

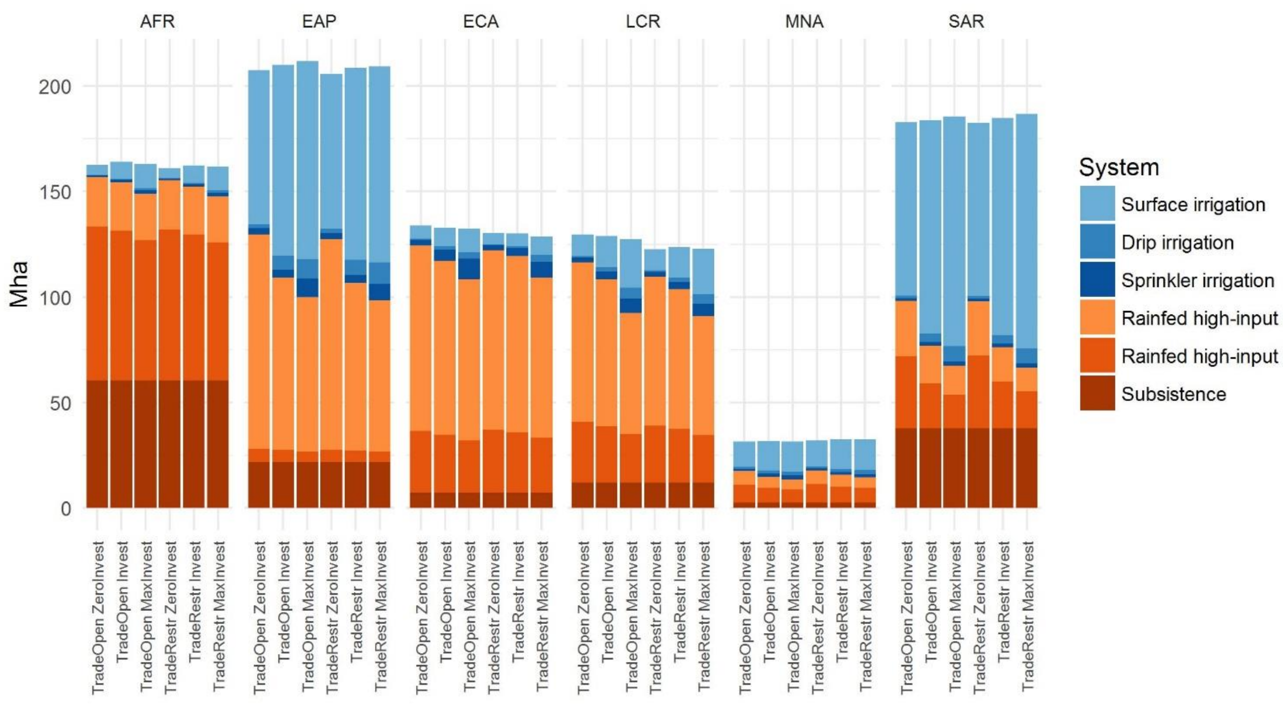

Figure SI 78. Cropland area by system under different international trade assumptions under *ZeroInvest*, *Invest* and *MaxInvest* in 2030 by region (Mha)

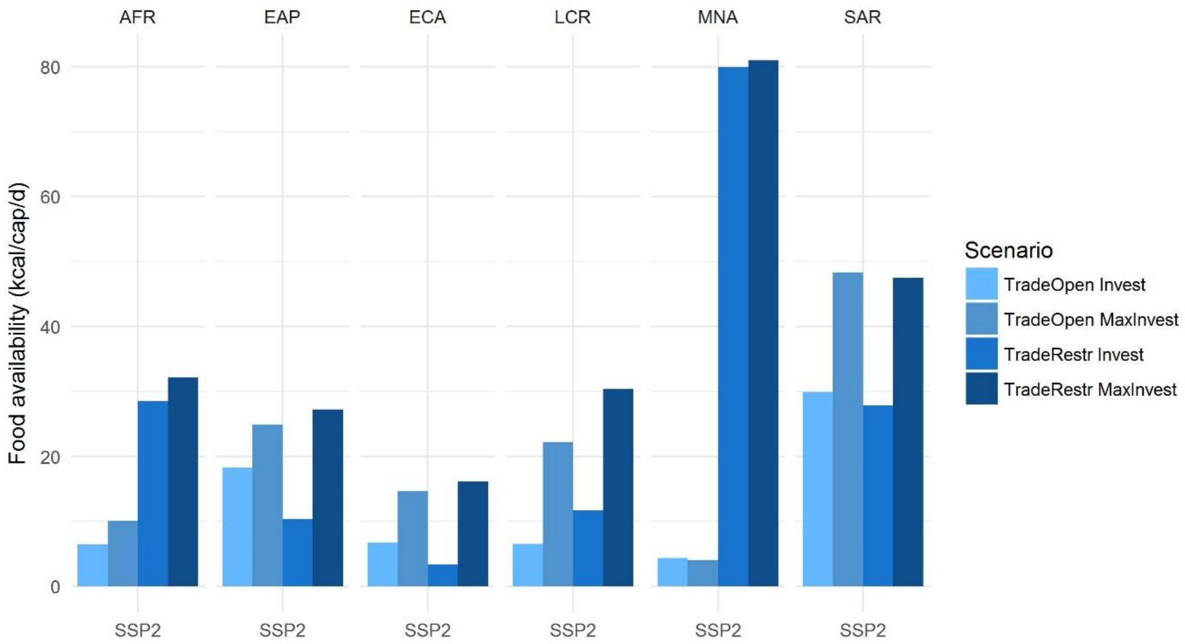

Figure SI 79. Change in food availability under different international trade assumptions compared to *ZeroInvest* in 2030 by region kcal/cap/day)

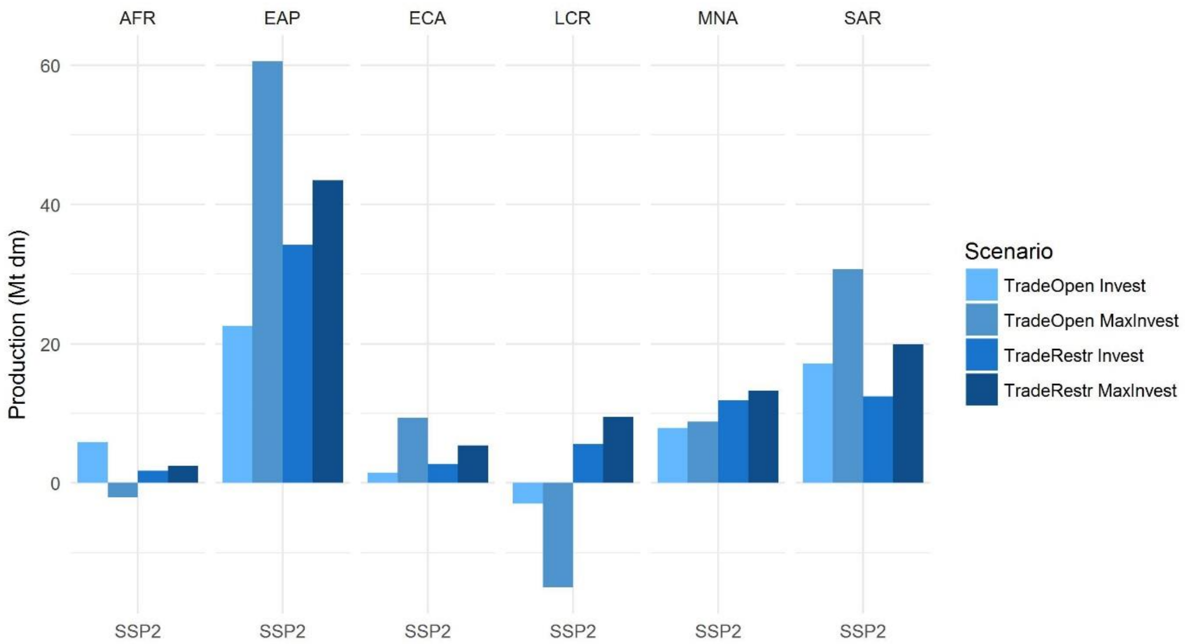

Figure SI 80. Change in crop production under different international trade assumptions compared to *ZeroInvest* in 2030 by region (Mt dm)

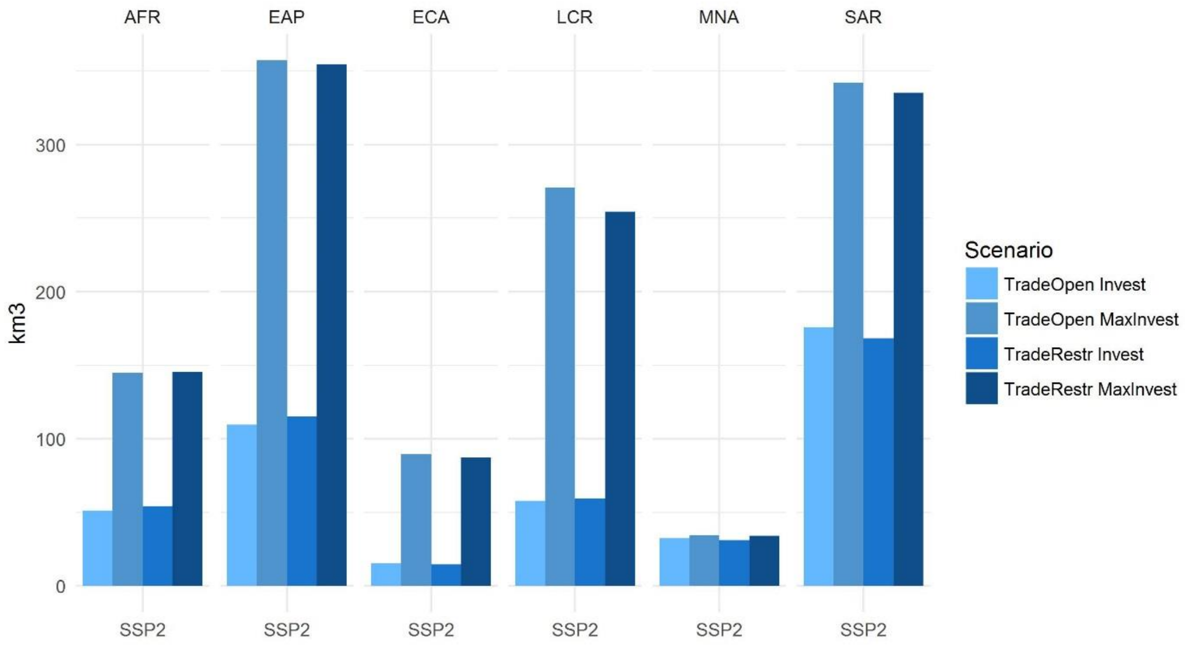

Figure SI 81. Change in water demand under different international trade assumptions compared to *ZeroInvest* in 2030 by region and scenario (km3)

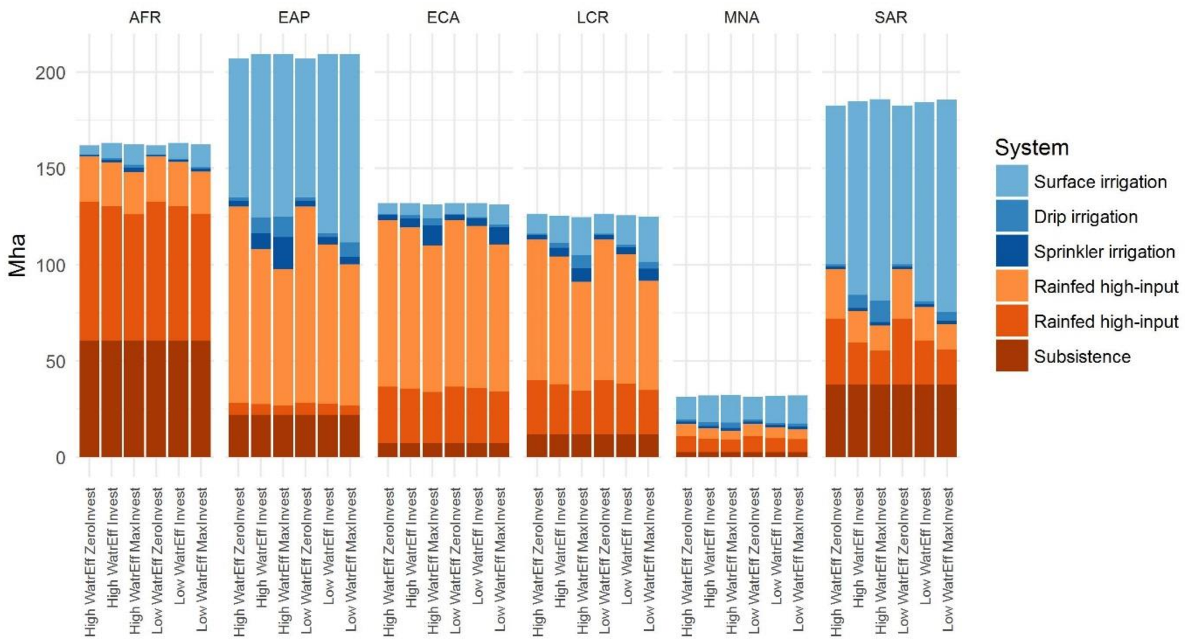

Figure SI 82. Cropland area by system under different international irrigation application efficiency assumptions under ZeroInvest, Invest and MaxInvest in 2030 by region (Mha)

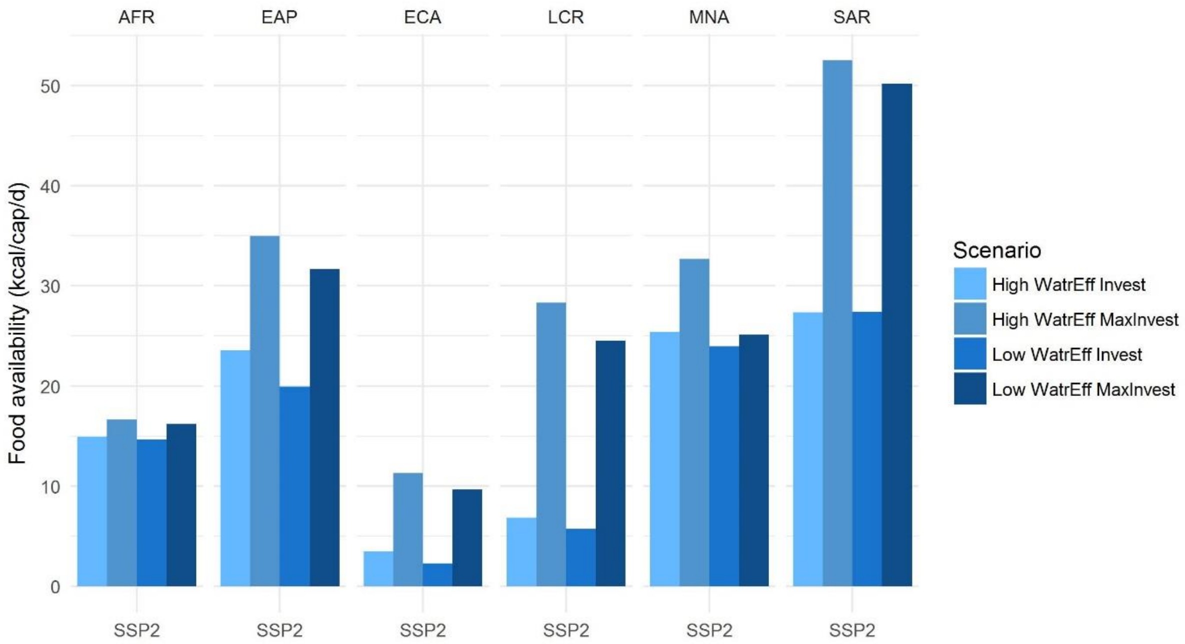

Figure SI 83. Change in food availability under different irrigation application efficiency assumptions compared to ZeroInvest in 2030 (kcal/cap/day)

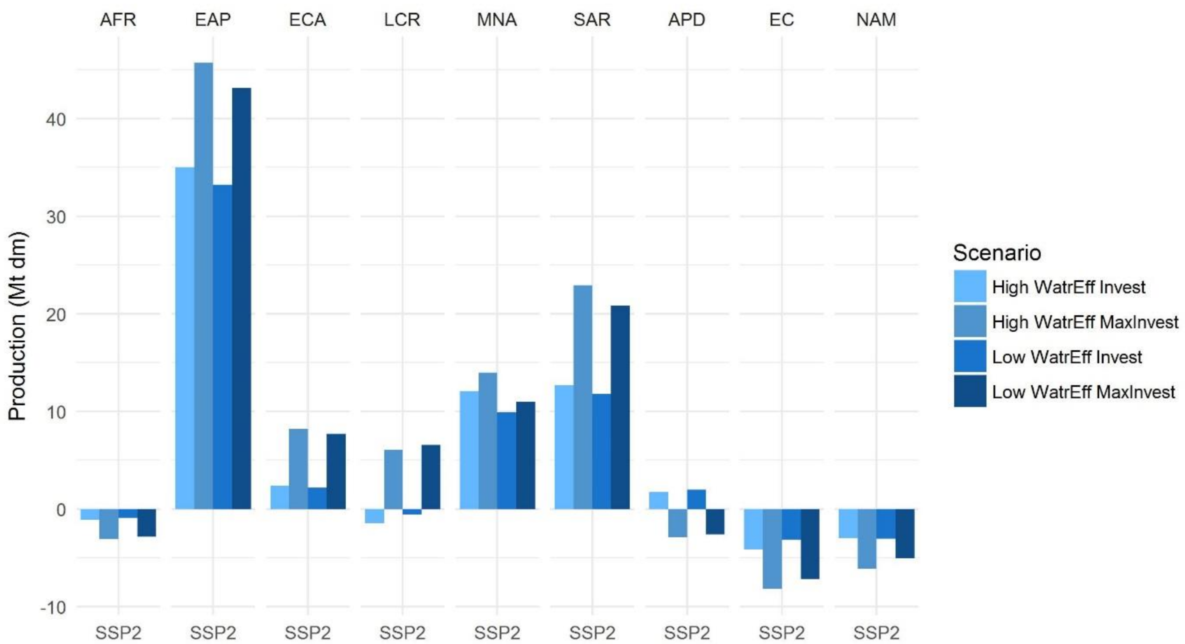

Figure SI 84. Change in crop production under different water application efficiency assumptions compared to ZeroInvest in 2030 by region (Mt dm)

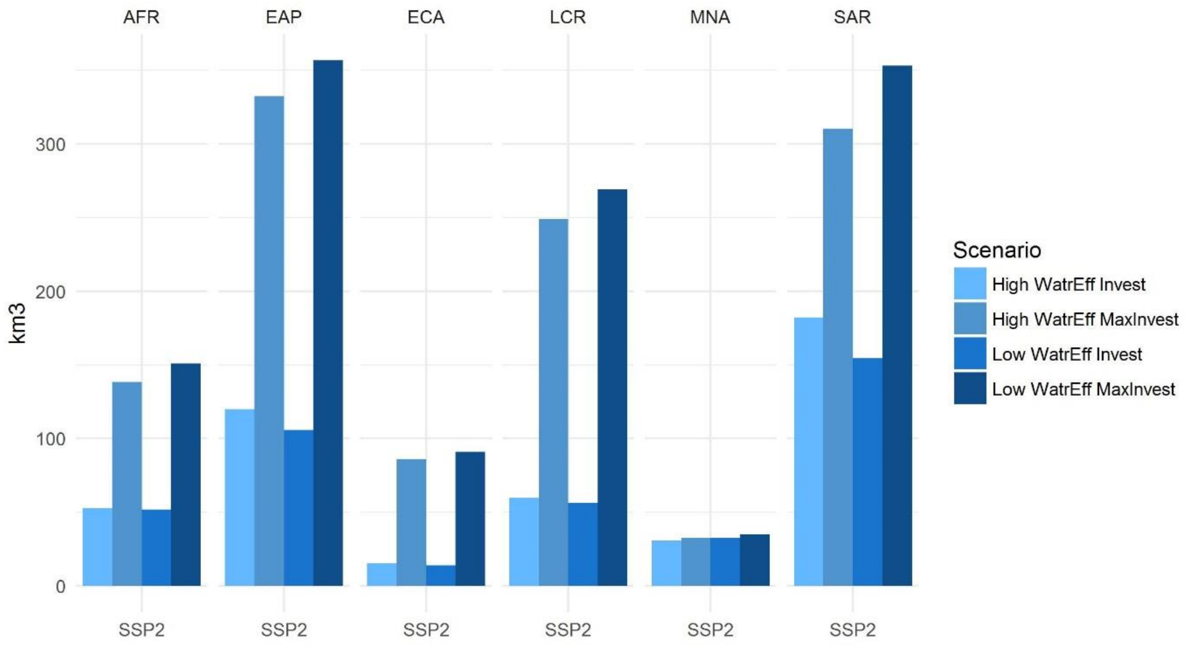

Figure SI 85. Water withdrawal for irrigation under different irrigation application efficiency assumptions in 2030 by region (km3)

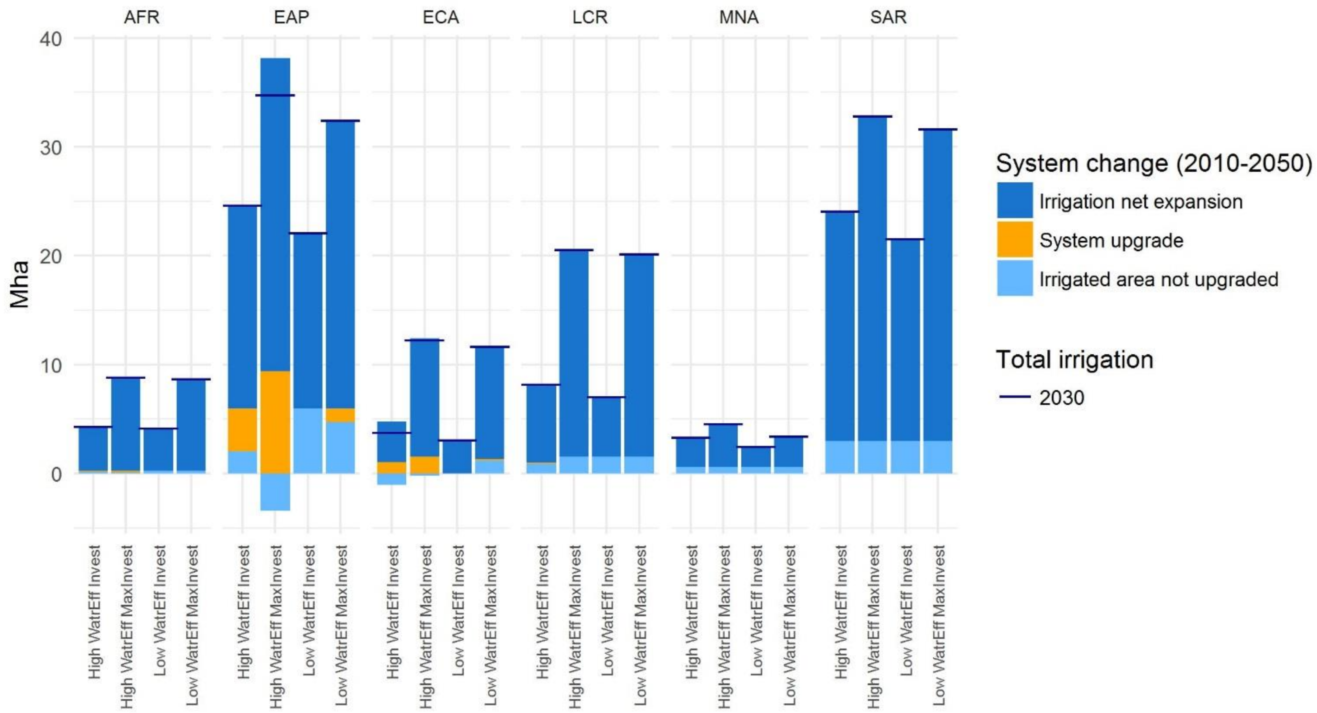

Figure SI 86. Cumulative irrigated area expansion and upgrade under various efficiency scenarios from 2010 to 2030 (Mha)

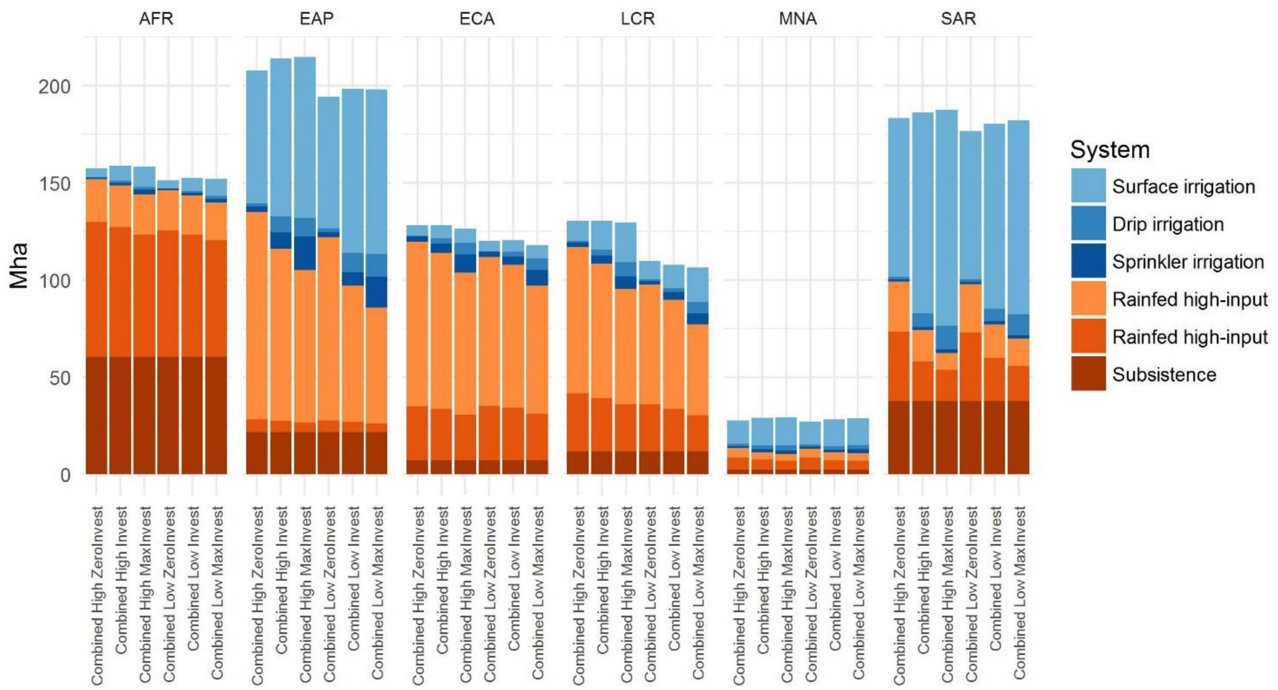

Figure SI 87. Cropland area by system under different combinations of uncertainty parameters under ZeroInvest, Invest, and MaxInvest by region in 2030 (Mha)

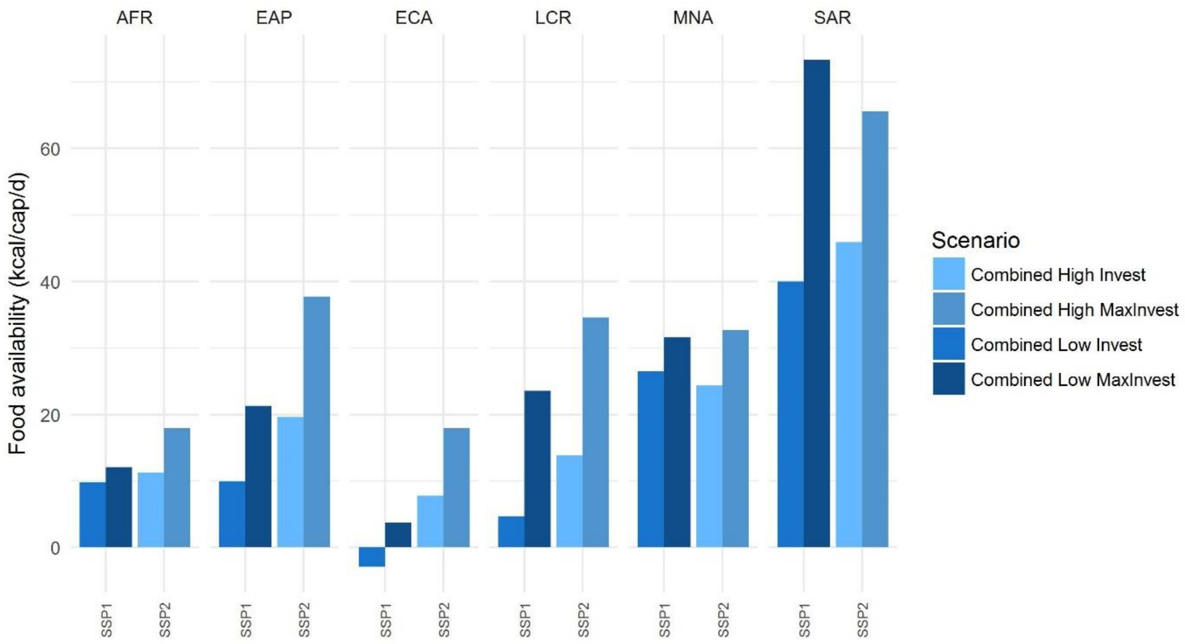

Figure SI 88. Change in food availability under different combinations of uncertainty parameters compared to *ZeroInvest* in 2050 (kilocalorie per capita per day)

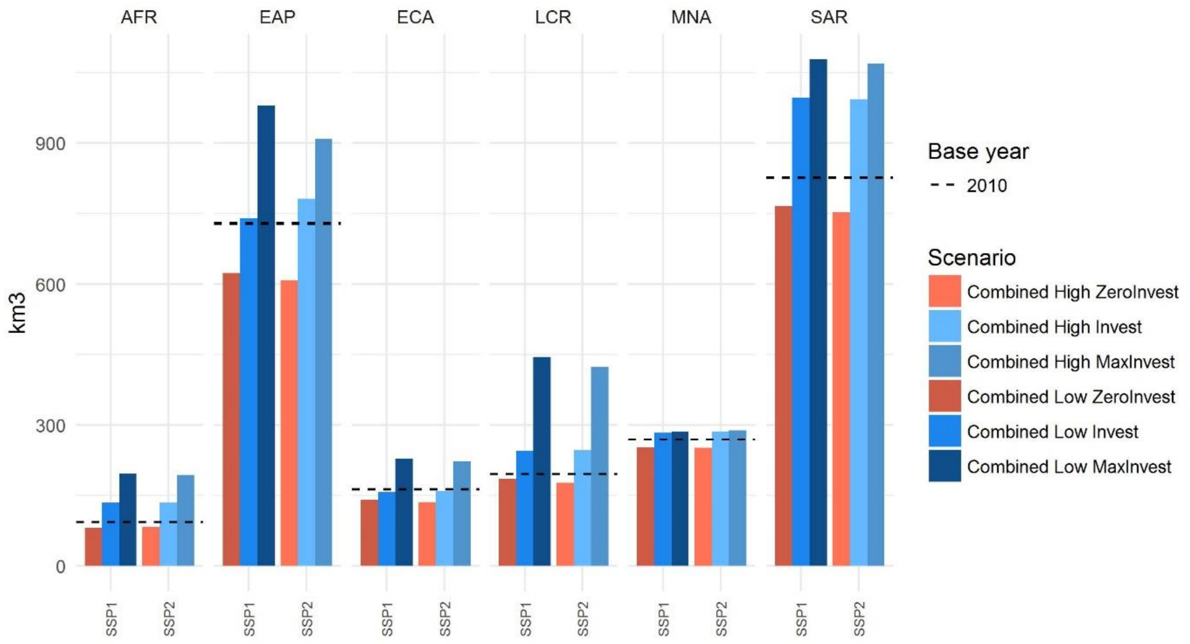

Figure SI 89. Water withdrawal for irrigation under different combinations of uncertainty parameters in 2050 by region (km3)

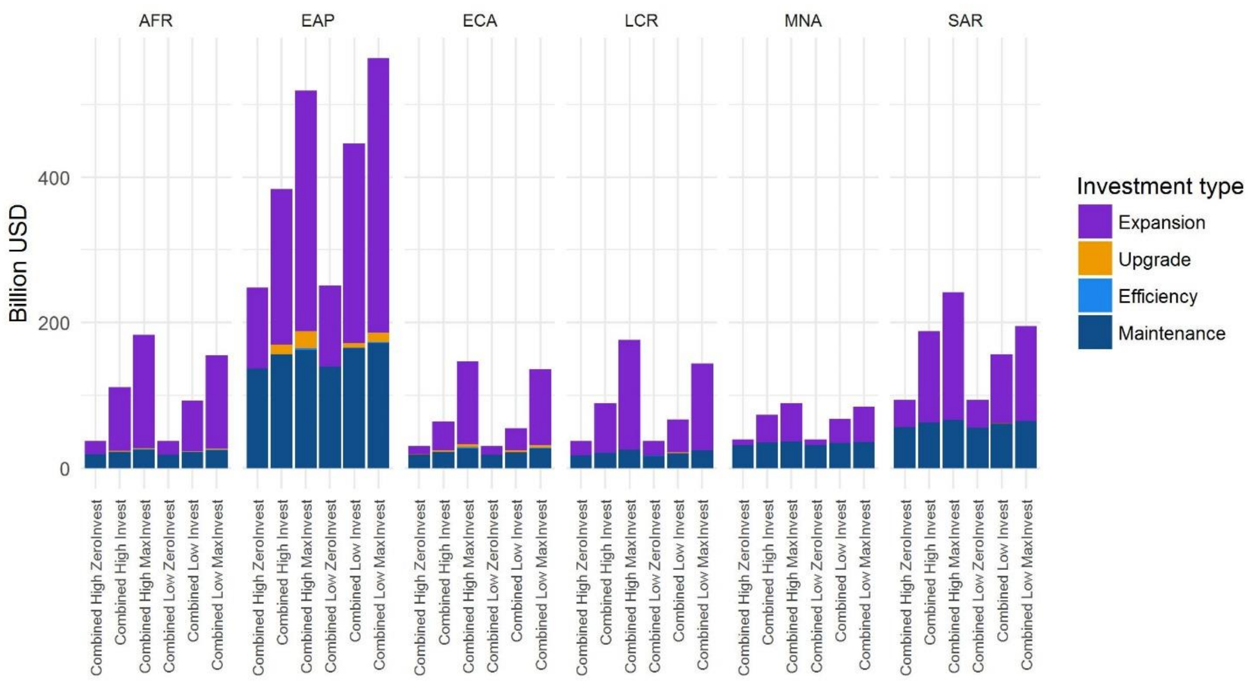

Figure SI 90. Cumulative developing country investment costs under different combinations of uncertainty parameters in 2050 by region ($ billion, 2000 US dollar)

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