Supplementary information: Uncertainty in land-use adaptation persists despite crop model projections showing lower impacts under high warming

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Supplementary Discussion 1: Overview of harmonized and calibrated crop model yields (Global and Regional)

For the RCP2.6 scenario, in 2100, compared with 2015 values, global average harmonized and calibrated yields of the four major crops (maize, temperate cereals, soybean, and rice) projected by the GCM-GGCMs (aggregated using constant crop areas as weight), the ensemble has a median relative change of +1.2% with an interquartile range (IQR) between +0.3% and +2.3%. The GCM-GGCM combinations located at the extremes of the range for RCP2.6 correspond to the CYGMA1p74-UKESM1-0-LL (CYGMA-UKESM) (-10%) and PROMET-MRI-ESM2-0 (-4.9%) (Figure 1a). On the other hand, relative changes in average projected crop yields have a higher uncertainty in the

RCP8.5 scenario (median=-3.8% and IQR=[-14%,+3.3%]) in 2100. Regarding the GCM-GGCM at the end of the range of this set, PROMET-MRI-ESM2-0 (PROMET-MRI) stays at the positive extreme with average gains of +28% in 2100 compared with 2015, and CYGMA-UKESM at the most negative with losses of -34% (Figure 1b). In terms of the most affected individual crops, and compared with 2015 values, for RCP2.6, the maize yields (irrigated median= -2.2% and IQR=[-5.2%,-0.7%], and rainfed median= -1.6% and IQR= [-4.9%,1.9%]) are expected to mildly decrease in productivity, while rainfed soybean yields (median= +4.2% and IQR= [-1.8%,+5.2%]) are expected to grow in 2100 slightly (Figure 1c). For RCP8.5, the largest losses in 2100 take place also for maize (irrigated median=-30% and IQR=[-50%,-14%], and rainfed median=-16% and IQR=[-40%,-2.3%]). Conversely, rainfed temperate cereals show a positive yield gain (median=+7.9% and IQR=[-4.6%,+15%]). Other crops' medians are between -12% and +1% (Figure 1d).

Regionally, for the RCP2.6 scenario, the United States (USA) displays the largest negative impacts (median=-0.54% and IQR=[-3.9%,+2.4%]) of the 13 regions considered in this study. This reduction in average yields is mainly driven by losses in the regional productivity of irrigated (median=-4.4% and IQR=[-8.8%,-1.2%]) and rainfed (median=-4.9% and IQR=[-7.6%,+0.84%]) maize. On the other hand, Canada (CAN) (median=+7.0% and IQR=[+3.2%,+8.4%]), and European countries not in the EU (NEU) (median=+4.2% and IQR=[+1.6%,+6.3%]) show the largest relative gains. Specifically, CAN sees gains in rainfed soybean (median=+8.4% and IQR=[+2.8%,+14%]), and in rainfed maize (median=+6.7% and IQR=[+0.67%,+9.4%]) (Supplementary Figures **1**a and **2**a). Finally NEU displays gains in rainfed temperate cereals (median=+6.0% and IQR=[+2.9%,+7.9%]) and soybean (median=+5.2% and IQR=[+3.2%,+6.5%]).

At the regional scale, in RCP8.5, the USA is again the most negatively impacted region (median=-16% and IQR=[-34%,+2.1%]), mostly due to an average decrease in the productivity of maize (irrigated median=-34% and IQR=[-57%,-16%], and rainfed (median=-23% and IQR=[-50%,-1.4%]). Australia and New Zealand (ANZ) is the region with the largest positive relative change (median=+12% and IQR=[+4.5%,+15%]) as a result of increases in rainfed soybean (median=+33% and IQR=[+2.7%,+66%]), and rainfed temperate cereals (median=+13% and IQR=[+4.7%,+16%) (Supplementary Figures **1**b and **2**b).

Another crucial biophysical input is blue water availability, given that agriculture is highly dependent on irrigation as a management practice and adaptation option. On the global level, the RCP2.6 scenario displays a relative change of water availability between -0.53% and +4.3% in 2100, compared with 2015 values (Supplementary Figure **3**a). At the regional scale, CAN ([+0.68%,+10%]), CHA ([+1.8%,+15%]), and the Middle East and Northern Africa (MEA) ([+9.4%,+26%]) exhibit gains in water availability for all of the GCMs in 2100. In contrast, agreement in losses of water availability across GCMs can be seen in ANZ ([-13%,-5.4%]) in 2100. For the remaining regions, GCM outputs oscillate between negative and positive values (Supplementary Figure **4**a). In the RCP8.5 case, all of the GCMs, besides MPI-ESM1-2-HR, show losses in available water ([-15%,+1.6%]) at the global scale in 2100 (Supplementary Figure **3**b). Regionally, water availability for all GCMs is expected to decrease in CHA ([-18%,-2.1%]), and EU European countries (EUR) ([-20%,-8.2%]) (Supplementary Figure **4**b).

Supplementary Discussion 2: Sources of uncertainty in crop model yields

Uncertainty displayed in the crop yields reported by the GGCMs derives from two primary sources and increases with emissions and time.[1] First, uncertainty is transferred from the climate models outputs (mostly warming and precipitation during the growing seasons) used as inputs by the crop models at the aggregated and spatially explicit levels. Climate model uncertainty is associated, among others, with the inherent complexity of the climate system, stochasticity of inputs and driving forces (e.g., volcanic eruptions), and the parametrization of processes due to computational constraints (e.g., cloud formation).[2] These translate into different climate sensitivities among the climate models for the same emissions scenario.

The second source of uncertainty comes from the GGCM's design, specifically, the parametrization of processes affecting the biosphere, their sensitivity to change, and the lack of empirical data for their calibration. For example, CO_2 fertilization, especially at high concentrations, appears as a large source of uncertainty due to missing empirical data.[1,3] More information about crop yield projections' variance and drivers can be found in Jägermeyer et al.[3] and Müller et al.[1]

Supplementary Discussion 3: Sensitivity Analysis

Similar to the climate and crop models, MAgPIE is also sensitive to uncertainties arising from inputs such as crop impact data, socio-economic projections, and assumptions, as well as the parametrization and interpretation of processes and storylines (e.g., the elasticity of demand, the definition of a sustainable food system, or the interpretation of a liberalized trading system). We conduct a sensitivity analysis to examine how alternative assumptions and scenarios could impact global adaptation responses. Specifically, we evaluated the effects on production costs, rainfed and irrigated cropland, and the TC factor (as shown in Supplementary Figures **14-16**) across three different GCM-GGCM sets of climate impacts under SSP5-RCP8.5: (1) CYGMA1p74-UKESM1-0-LL (the simulation with the most negative average impacts on yields), (2) PROMET-MRI-ESM2-0 (the simulation with the most positive impacts), and (3) LPJmL-MRI-ESM2-0 (MAgPIE's default). We evaluated a scenario considering elastic food demand and scenarios with larger and lower values than our defaults for depreciation rate, R&D costs' elasticity, trade liberalization, and available water for environmental purposes. The specific variations made for each scenario are presented in Supplementary Table **1**. We found that the sensitivity analysis scenarios have a relatively greater impact on irrigated cropland than other adaptation mechanisms. Since the amount of irrigated cropland is considerably less than that of rainfed, even small changes show a larger relative difference. However, as noted in the main manuscript, irrigation has a lower effect on adaptation and the supply-demand balance than rainfed cropland expansion and technological change (TC). Regarding the different GGCMs, CYGMA1p74-UKESM1-0-LL shows the biggest differences among the sensitivity analysis scenarios. The largest difference between the scenarios and their corresponding SSP5-NoCC compared to the default difference is around -14 percentage points in 2100, which corresponds to irrigated cropland. Differences in percentage points remain below 10 points for the rest of the scenarios. For PROMET-MRI-ESM2-0 the differences between the scenarios and their corresponding SSP5-NoCC are very similar to those of the default settings, except for irrigated cropland. The largest difference at the end of the century is seen when selecting endogenous food demand (demand for agricultural commodities is affected by consumer prices) for irrigated cropland (-11% compared to -19% of the default). Although overall crop demand does not change, there are modest changes in the crop production allocation, leading to slightly different regional crop patterns and irrigation requirements.

Finally, for LPJmL-MRI-ESM2-0, there are no large differences among the scenarios. Only the 7% depreciation and the globalized trade scenario (where 90% of crop products from 2050 are traded based on competitiveness rather than fixed trading flows) scenarios cause slight differences in 2100 (above two percentage points) for irrigated cropland compared to the default scenario. These scenarios support and emphasize our results. As the size of impacts grows due to increasing emissions, the uncertainty in changes in temperature and precipitation, changes in yields, and adaptation responses also increase.

Supplementary Methods 1: Parametrization

Given that MAgPIE is a global land allocation model that combines socio-economic and biophysical factors, cropland area and patterns (crop mixes) are directly affected by the demand for agricultural commodities for feed, food, and bioenergy uses, together with the competition with different land cover uses. Besides crop yields, production allocation, and available area, agricultural production, its costs, and the adaptiveness of the agricultural system are also constrained by (1) existing capital in agriculture, (2) the degree of trade openness of regions and countries, (3) land conversion costs, (4) investments in research and technology and (5) investments in irrigation systems. Further descriptions of these drivers (equations and parametrization) and additional modules can be found in the MAgPIE model documentation.[4]

Regarding capital stocks in agriculture, their location and depreciation rate are crucial in determining the speed at which production can be relocated, i.e., it determines the system's inertia, given that sunk capital could be placed in locations with unfavorable or less favorable climatic conditions. In specific contexts, depreciation can be lower than the rate of change, slowing down the transformation needed by the system.[5] MAgPIE accounts for long-lived capital investments (as capital stocks) and their depreciation through a version of the perpetual inventory method. MAgPIE decides investments made in the capital at each time step based on production requirements for each crop, region, and existing capital and its depreciation. This prevents the model from freely and instantaneously relocating production to more suitable locations based on better climatic conditions and from sudden shifts in crop mixes at the spatially explicit level. In turn, this captures a more realistic adaptation behavior. MAgPIE's default average depreciation rate is 5% since we assume a linear 20-year depreciation of assets.

Trade creates a bridge between regions with food production deficit and surplus and allows regions to concentrate on those crops where they have a comparative advantage. In this way, trade is key to increasing the adaptiveness of the global food system.[6] In MAgPIE, international trade is based on fulfilling regional demand via two pools (detailed information in Schmitz et al.[7]). One pool depends on historical self-sufficiency ratios (which fraction of internal demand is produced domestically for demand countries) and export shares (share of each region in global exports for each agricultural commodity for exporting countries). In the second pool, a "comparative advantage pool," production is freely allocated considering how cost-efficient the exporting regions are (e.g., crop rotation, more water availability, and lower production costs). Liberalization of the market is then simulated through an increase in the share of the trade volume that is distributed in accordance with historical trade patterns (self-sufficiencies and export shares). A share of one means that all exports end up in the first pool (historical trade patterns) and a share of zero in the second (complete freedom to relocate production to the most competitive regions). This share varies depending on the exogenous scenario assumption. Given that SSP1 and SSP5 consider high international trade, we assume that the percentage freely located in more competitive regions will reach 20% 2050 for livestock and secondary products and 30% for all other traded commodities in 2050. The effects of different trade assumptions under climate change in MAgPIE were compared by Stevanović et al. in.[8]

While trade and capital allocation affect the relocation of production to areas with competitive advantages, crop yields and production patterns are directly impacted by improvements and the introduction of technologies and management. Specifically, since the end of the 19th century, technological change has been the main method to increase agricultural output per hectare, reducing the pressure on cropland expansion.[9] We measure humans' effect on yields through technology, and management improvements by the agricultural land-use intensity, which we define as the ratio between observed yields and LPJmL yields simulations assuming homogeneous management intensity worldwide.[10] MAgPIE endogenously decides on the optimal technological change factor (TC) needed to proportionally increase agricultural land-use intensity considering the costs connected to investments in R&D and infrastructure. This relationship is based on the work of Dietrich et al.[9,10] where IPFRI, GTAP, and FAO data are used to determine the elasticity between TC and the investments yield ratio (which represents the investments required per-human-induced unit of yield growth in $US05\$/ha$). Currently, MAgPIE uses an average elasticity of 2.4. but counts with two additional scenarios based on Dietrich et al.'s regression: A low R&D costs scenario with an elasticity of 1.5 and a high costs one with an elasticity of 3.3, which we used for the sensitivity analysis.

Cropland expansion can also increase crop output and affects adaptation potentials, and is subject to competition with other land types and environmental goals (e.g., land protection for biodiversity and GHG targets), as well as land expansion costs. MAgPIE's allocation of cropland is determined by the overall dynamics of the system driven by demand, the minimization of costs, and the assumptions in land protection policies. Specifically, cropland change enters the costs function via expansion and reduction costs per hectare converted. Given the lack of region-specific information on these costs, MAgPIE counts with a calibration routine that determines the costs per hectare based on cropland historical trends. A further explanation of land conversion costs for other land types and the data sources used in MAgPIE can be found in Kreidenweis et al.[11] Finally, irrigation plays a crucial role in enhancing crop yields, particularly in areas with limited rainfall. In MAgPIE, irrigation is determined by several factors, including the yields of irrigated crops, the availability of existing irrigation infrastructure, water demand, and availability for agriculture, as well as the costs associated with investing and operating new crop irrigation facilities. LPJmL provides yields for irrigated crops, water demand for each crop, and overall blue water availability. On the one hand, demand for the domestic and industrial sectors and a 5% of water flow spare for environmental reasons are exogenously determined and restrict the final available water for agricultural use. On the other hand, it is assumed that irrigation can only occur where irrigation infrastructure is located, initial values of irrigated land are based on the LUH dataset,[12] and the decision to expand it is endogenously taken and depends on cost competitiveness. The costs per hectare of investing and operating new irrigation infrastructure are based on the world bank data and given at the regional level. However, regional costs are assumed to converge linearly to cost levels in Europe by 2050. A detailed explanation of the data sources, costs, and irrigation implementation in MAgPIE can be found in Bonsch et al.[13]

Supplementary Tables & Figures

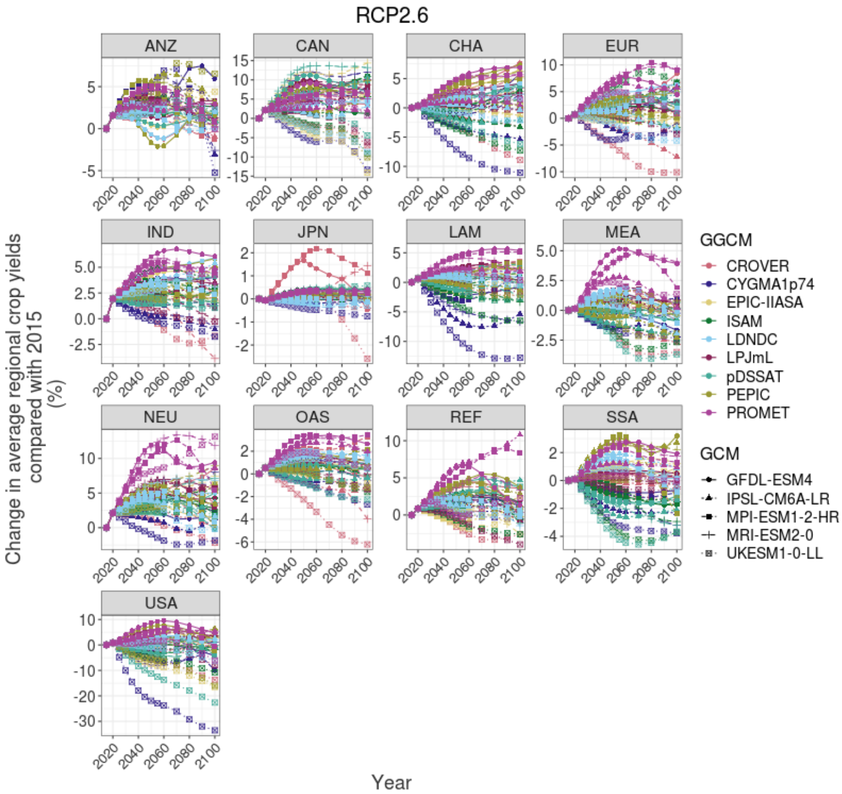
Sensitivity analysis scenarios

Supplementary Table 1: Assumptions changed for the sensitivity analysis of MAgPIE responses to different scenarios)

Scenario Setting	Default	Scenario 1	Scenario 2
Depreciation rate for capital	5%	3%	7%
Endogenous food demand	OFF	ON	x
R&D costs (elasticity)	medium (2.4)	high (3.3)	low (1.5)
Trade liberalization (% freely located in more competitive regions)	Reaches 20% for livestock and secondary products, and 30% for all other traded commodities in 2050, until 2100	(Regional) Reaches 5% for livestock and secondary products, and 10% for all other traded commodities in 2050, until 2100	(Globalized) Reaches 50% for livestock and secondary products, and 60% for all other traded commodities in 2050, until 2100
Available Water saved for environmental uses	5%	0%	10%

Figures for harmonized and calibrated biophysical impacts of climate change (Global and Regional)

a



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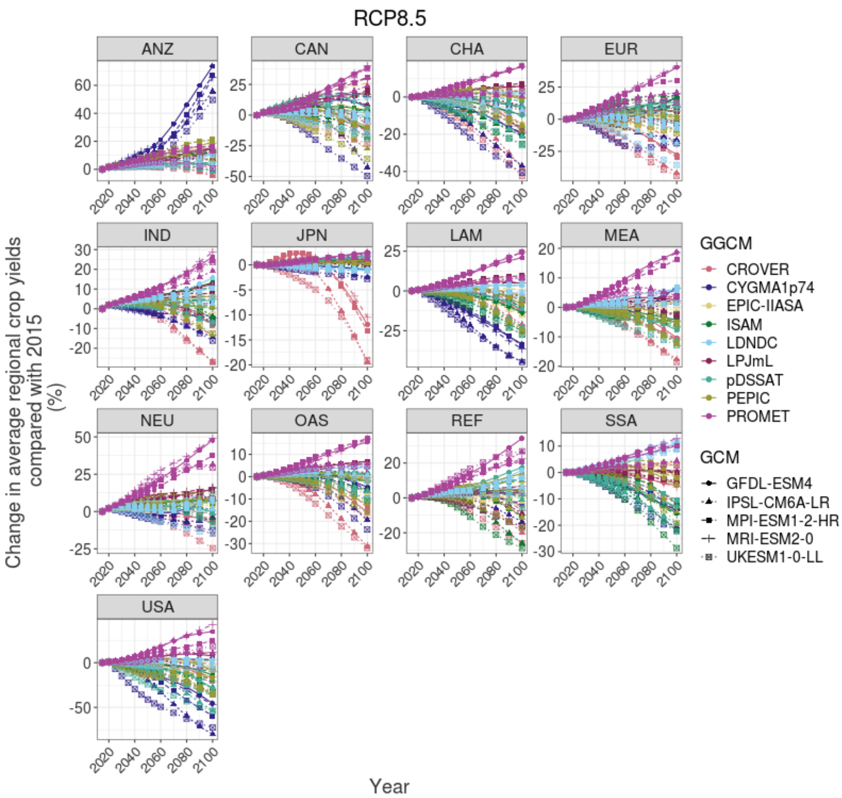

Supplementary Figure 1: **Relative change in regional aggregated crop yields for the complete ensemble of GCM-GGCM projections.** a) Shows combined effects for SSP1-RCP2.6 (sustainable) and b) for SSP5-RCP8.5 (fossil-fueled development) comparing yearly results with 2015 values

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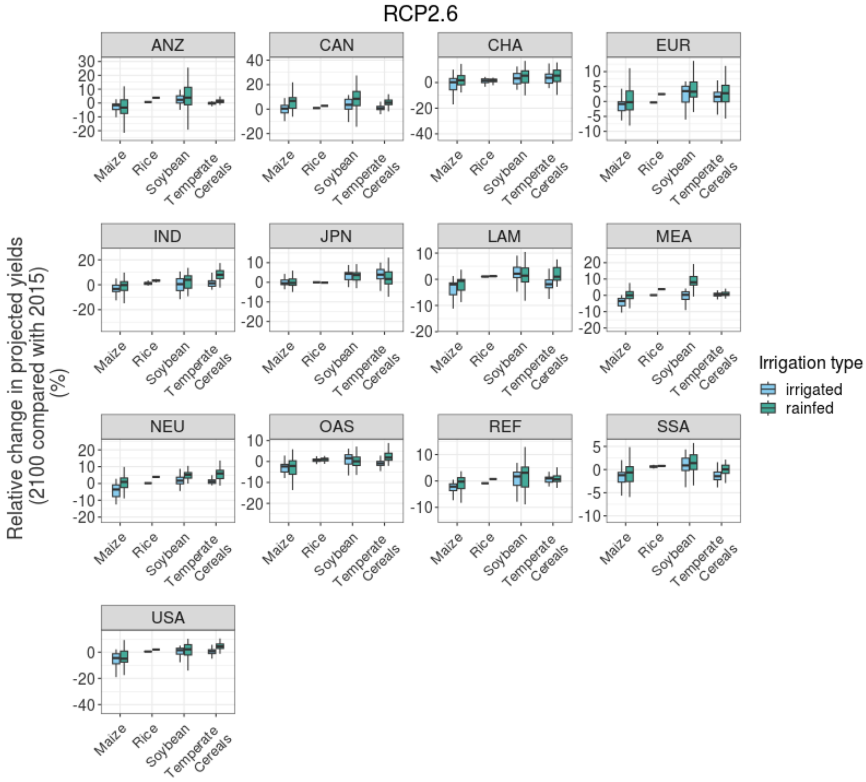

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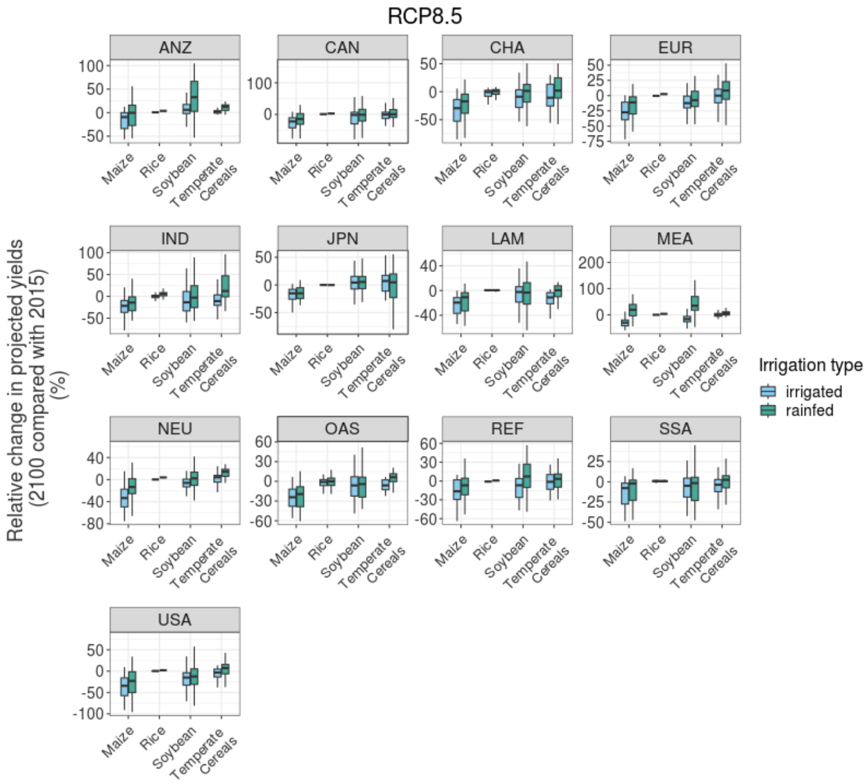
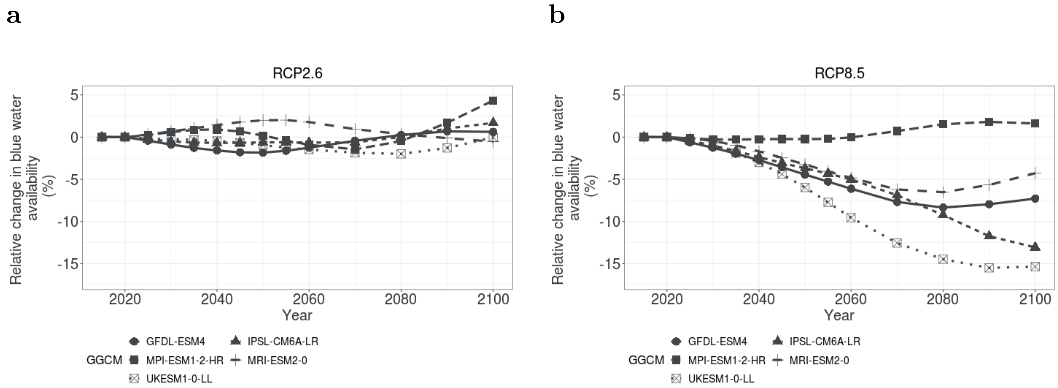
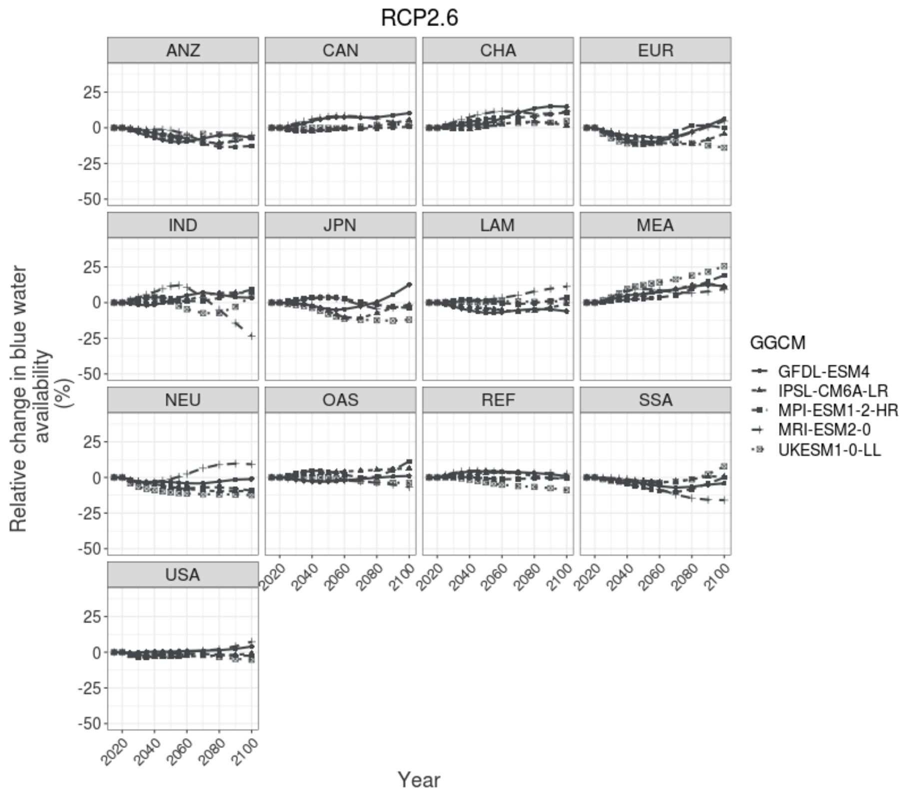


Supplementary Figure 2: **2100 regional distribution of relative change in aggregated crop yields for the ensemble of GCM-GGCM impact projections on yields, compared with 2015, for four major crops (maize, soybean, rice, wheat) using box plots and differentiating between irrigated and rainfed.** a) SSP1-RCP2.6 and b) SSP5-RCP8.5. and for the GCM-GGCM ensemble of projections. The horizontal solid line represents the median, the box the interquartile range, and the vertical lines extend from the lowest to the largest values of the GGCM-GGCM ensemble



Supplementary Figure 3: **Global climate change impacts on blue water availability (surface and groundwater reservoirs) for RCP2.6 and RCP8.5 scenarios.** a) and b) show the relative change in blue water availability simulated by LPJmL for different climate models compare to 2015 values.

a



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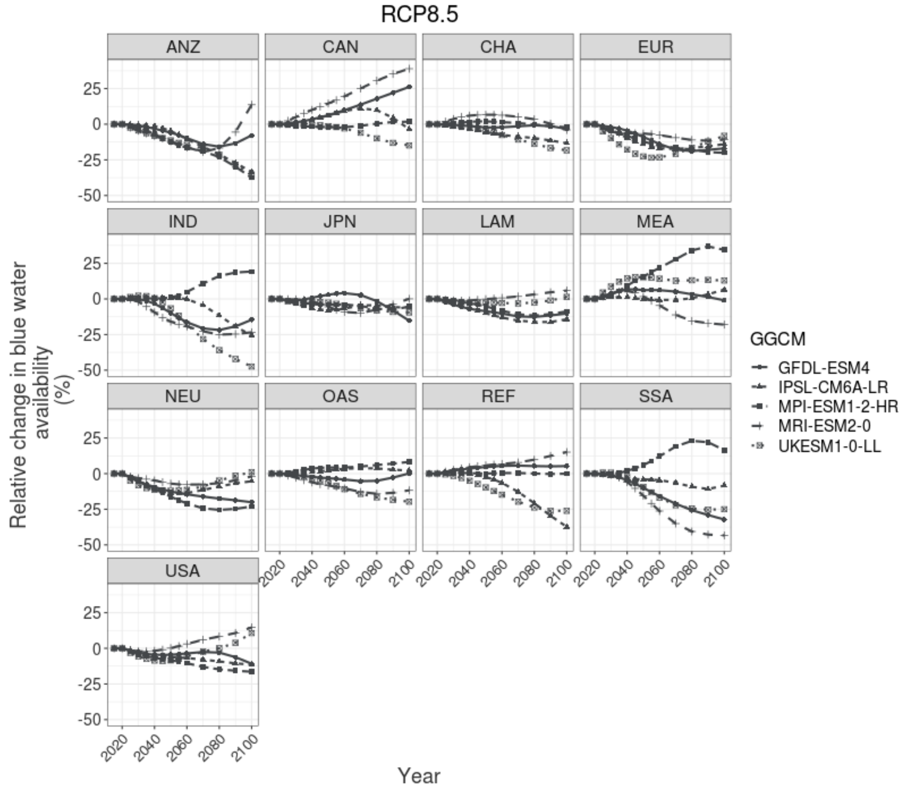
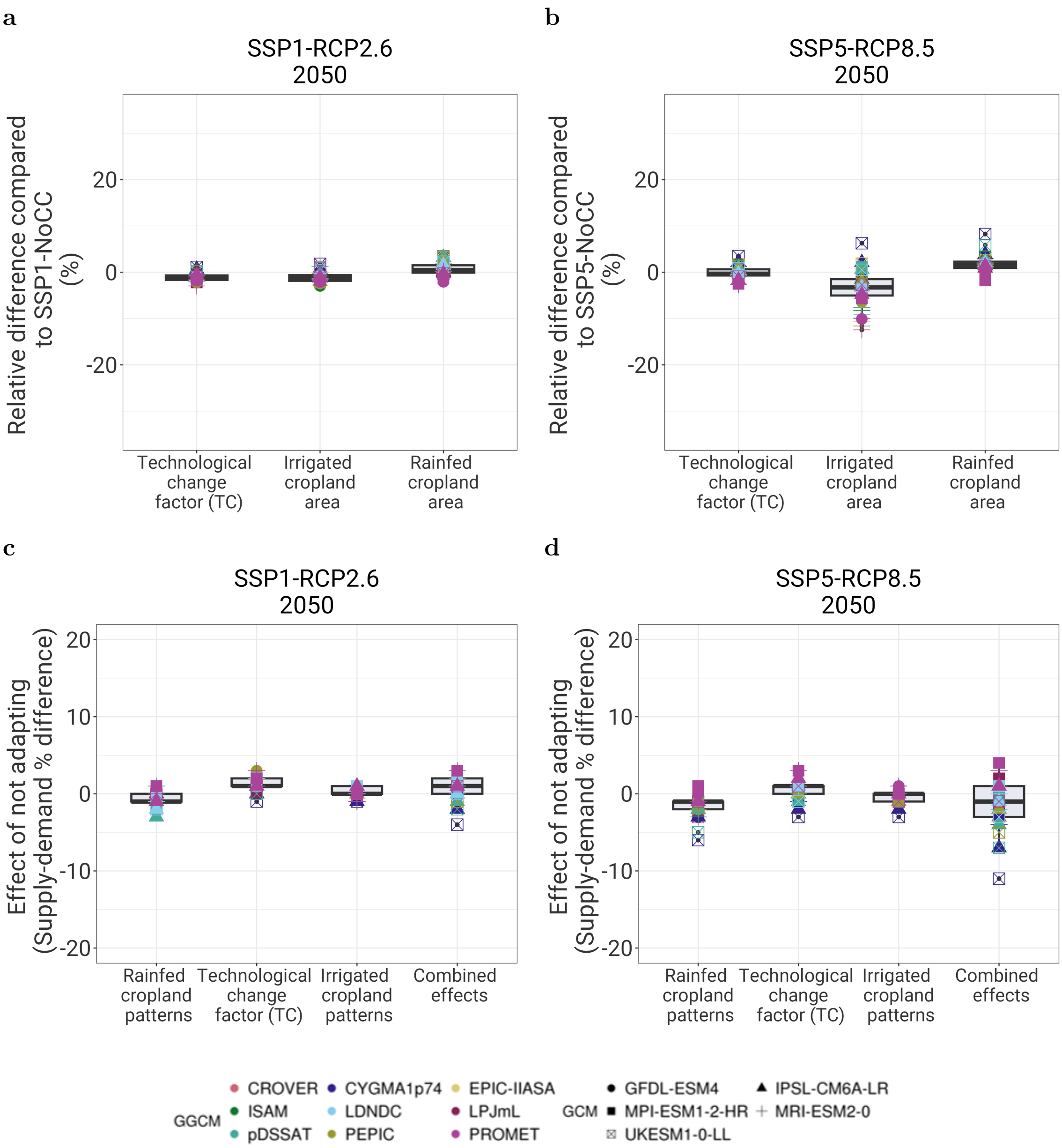


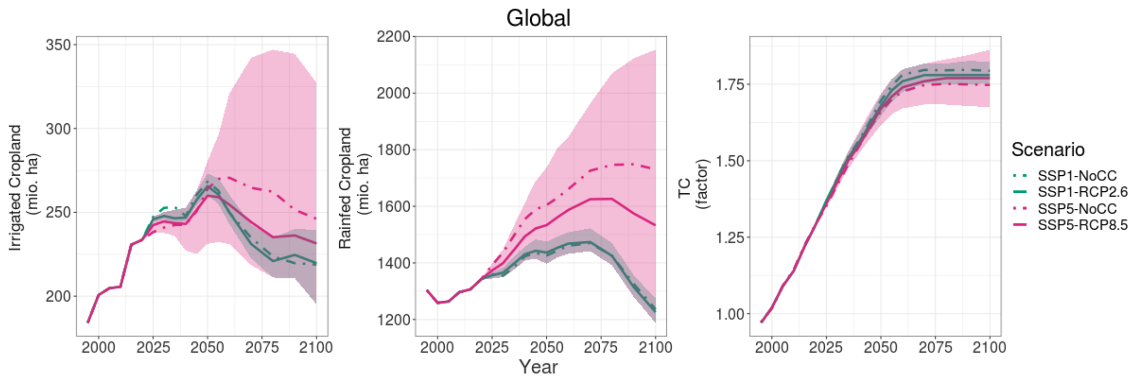
Supplementary Figure 4: **Regional change in blue water availability projected by LPJmL and different climate models.** a) SSP1-RCP2.6 (sustainability) and b) SSP5-RCP8.5 (fossil-fueled scenario)

Climate change driven adaptation in 2050

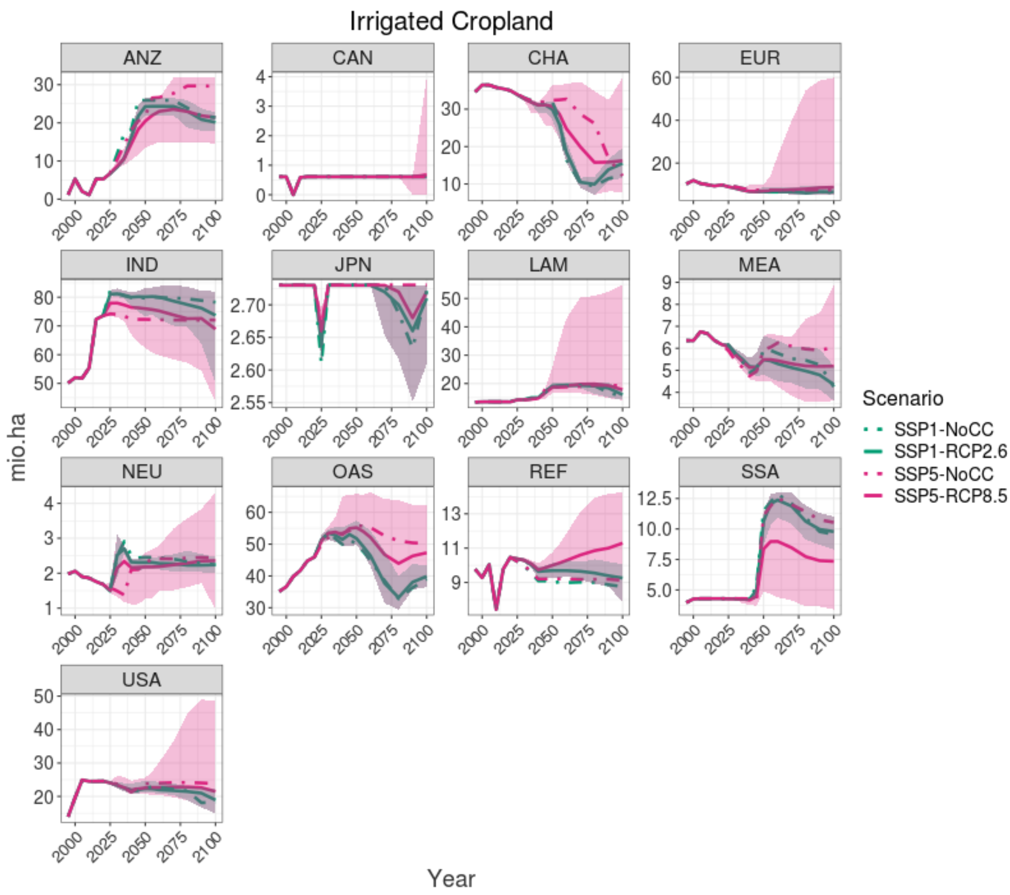


Supplementary Figure 5: Global climate change adaptation responses in the MAgPIE model under SSP1-RCP2.6 (low emissions) and SSP5-RCP8.5 (high emissions) scenarios in 2050: a) and b) show the relative difference of (TC)* and rainfed and irrigated cropland areas values for SSP1-RCP2.6 and SSP5-RCP8.5 scenarios with respect to the socio-economic scenarios without climate impacts, i.e., SSP1-NoCC and SSP5-NoCC. c) and d) depict the individual and combined effects of not adapting cropland patterns and TC to climate change. These effects are calculated in a post-processing step as the relative difference between impacted production (calculated using SSPx-NoCC's TC and/or cropland patterns with harmonized and calibrated GCM-GGCM impacted crop yield projections) and SSPx-RCPy demand. *The TC factor produces a proportional increase in crop yields based on investments in management and R&D.The horizontal solid line represents the median, the box the interquartile range, and the vertical lines extend from the lowest to the largest values of the GGCM-GGCM ensemble.

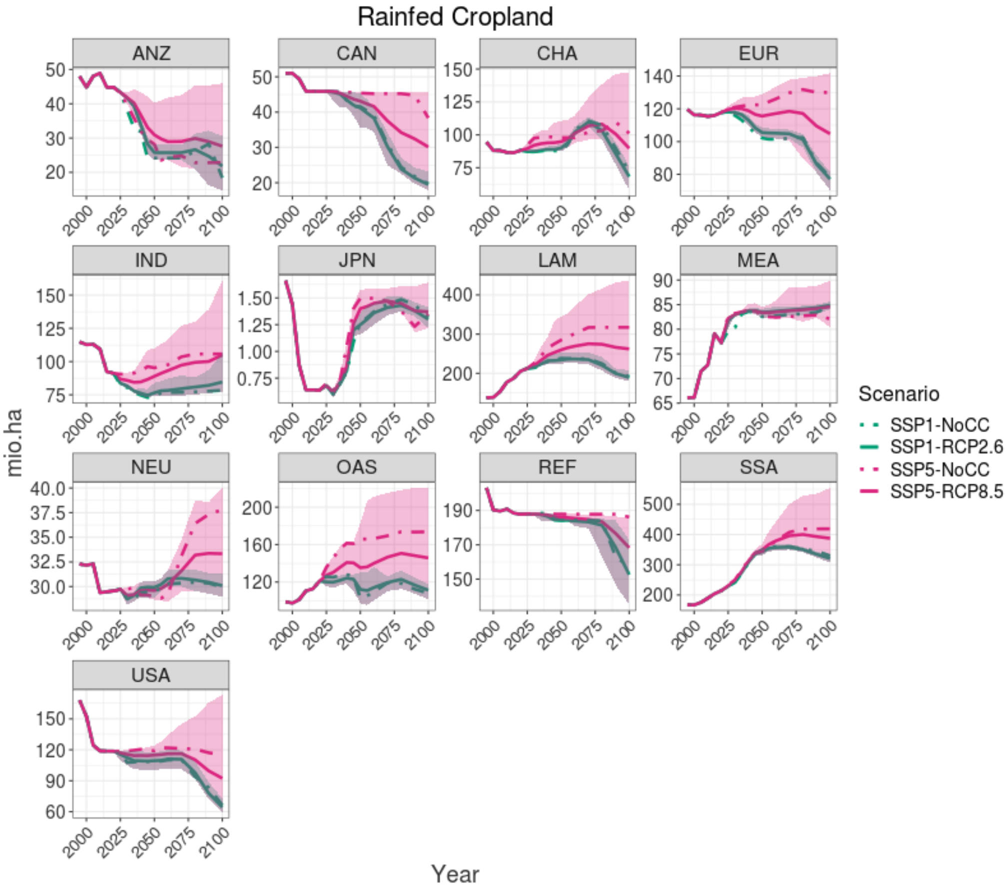
Global and Regional Land-use time series



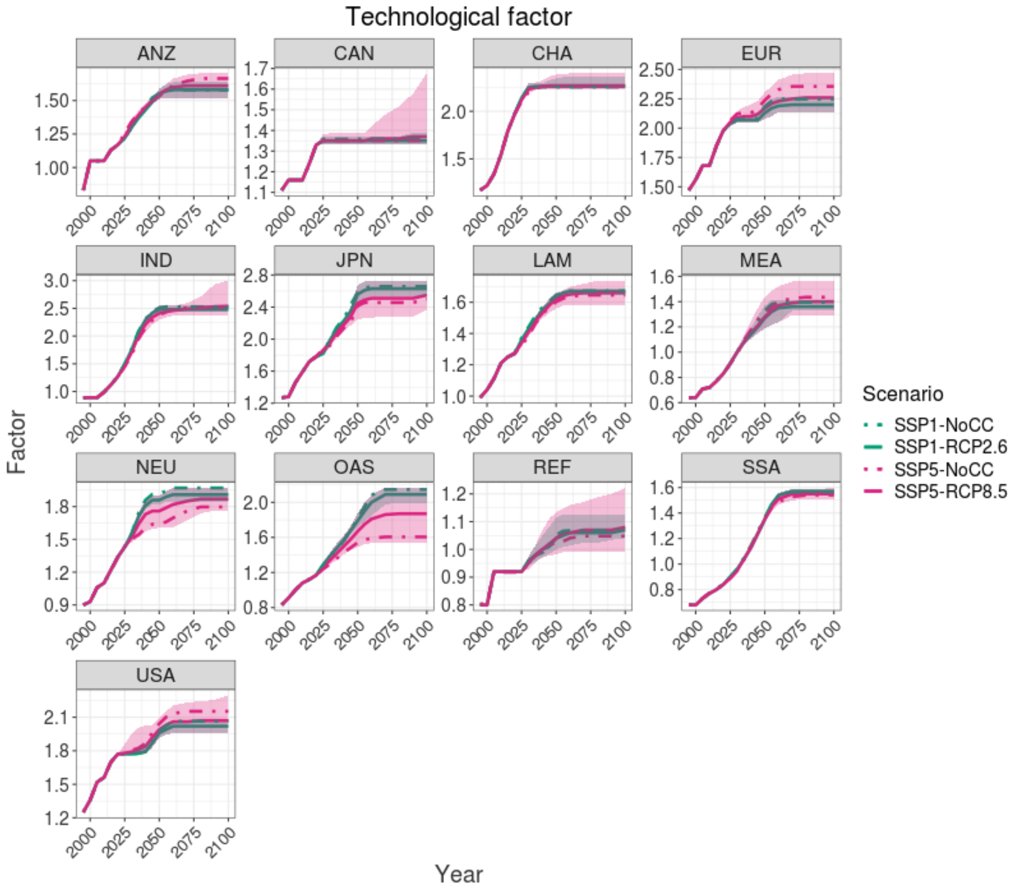
Supplementary Figure 6: **Time series of global trajectories of the factor of technological change, and irrigated and rainfed cropland for SSP1-RCP2.6 and SSP5-RCP8.5** The color dark pink represents scenarios related to SSP5, while green represents SSP1. The solid line indicates the average of the MAgPIE outputs based on the ensemble of GCM-GGCM combinations for the SSPx-RCPy scenarios. In contrast, the dotted lines display the SSPx-NoCC scenarios, where socio-economic changes are considered, but biophysical variables, such as crop yields and water availability, are fixed at 2015 levels. The shaded areas represent the minimum and maximum values of the MAgPIE outputs.



Supplementary Figure 7: **Time series of regional trajectories of irrigated cropland for SSP1-RCP2.6 and SSP5-RCP8.5 scenarios.** The color dark pink represents scenarios related to SSP5, while green represents SSP1. The solid line indicates the average of the MAgPIE outputs based on the ensemble of GCM-GGCM combinations for the SSPx-RCPy scenarios. In contrast, the dotted lines display the SSPx-NoCC scenarios, where socio-economic changes are considered, but biophysical variables, such as crop yields and water availability, are fixed at 2015 levels. The shaded areas represent the minimum and maximum values of the MAgPIE outputs.



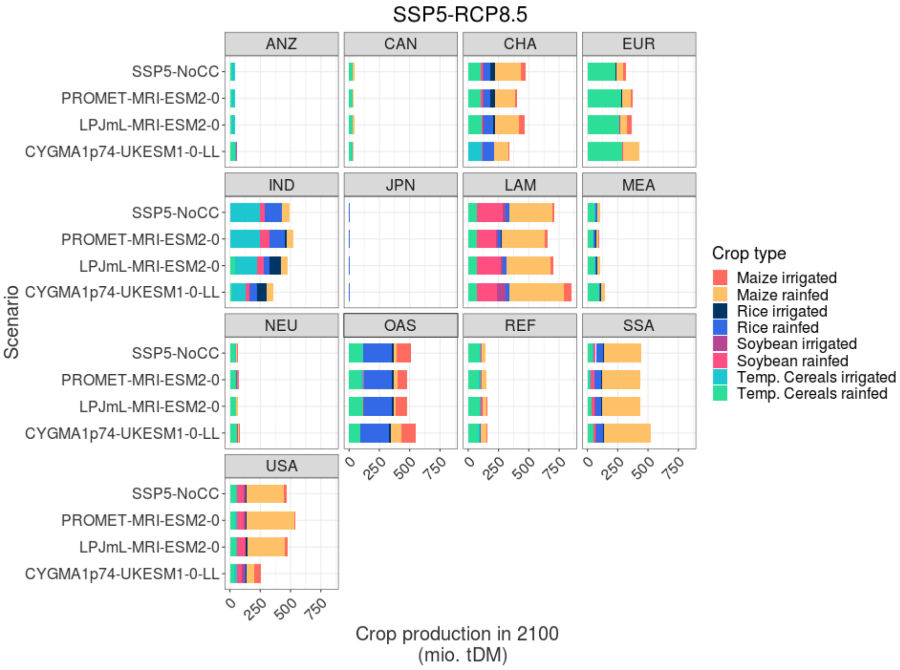
Supplementary Figure 8: **Time series of regional trajectories of rainfed cropland for SSP1-RCP2.6 and SSP5-RCP8.5 scenarios.** The color dark pink represents scenarios related to SSP5, while green represents SSP1. The solid line indicates the average of the MAgPIE outputs based on the ensemble of GCM-GGCM combinations for the SSPx-RCPy scenarios. In contrast, the dotted lines display the SSPx-NoCC scenarios, where socio-economic changes are considered, but biophysical variables, such as crop yields and water availability, are fixed at 2015 levels. The shaded areas represent the minimum and maximum values of the MAgPIE outputs.



Supplementary Figure 9: **Time series of regional trajectories of the technological change factor for SSP1-RCP2.6 and SSP5-RCP8.5 scenarios.** The color dark pink represents scenarios related to SSP5, while green represents SSP1. The solid line indicates the average of the MAgPIE outputs based on the ensemble of GCM-GGCM combinations for the SSPx-RCPy scenarios. In contrast, the dotted lines display the SSPx-NoCC scenarios, where socio-economic changes are considered, but biophysical variables, such as crop yields and water availability, are fixed at 2015 levels. The shaded areas represent the minimum and maximum values of the MAgPIE outputs.

Crop and Livestock regional production

a



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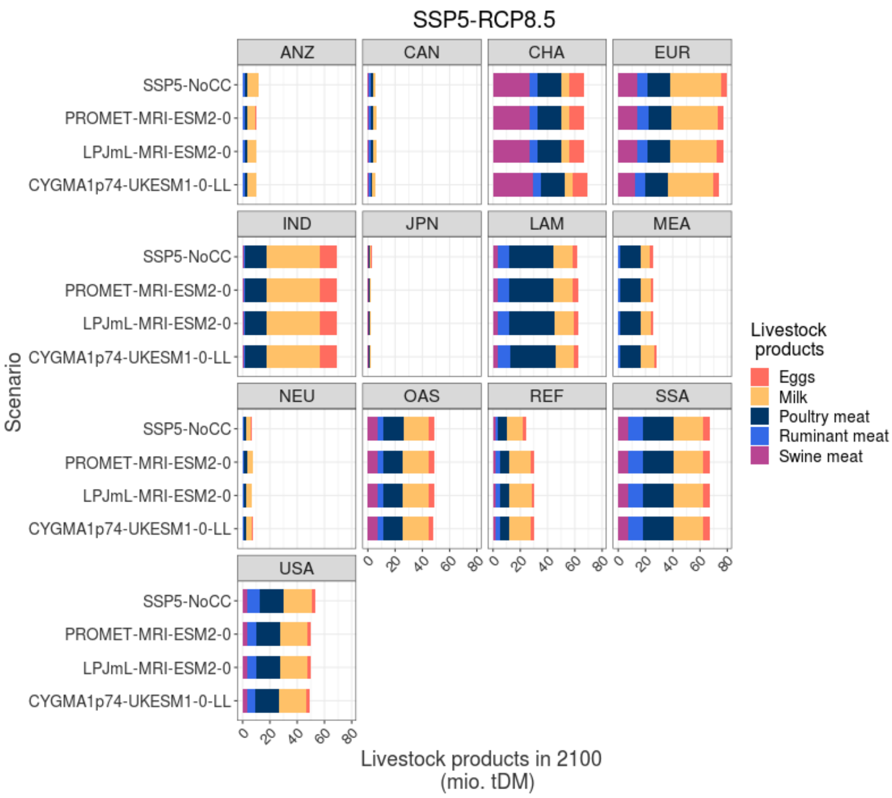
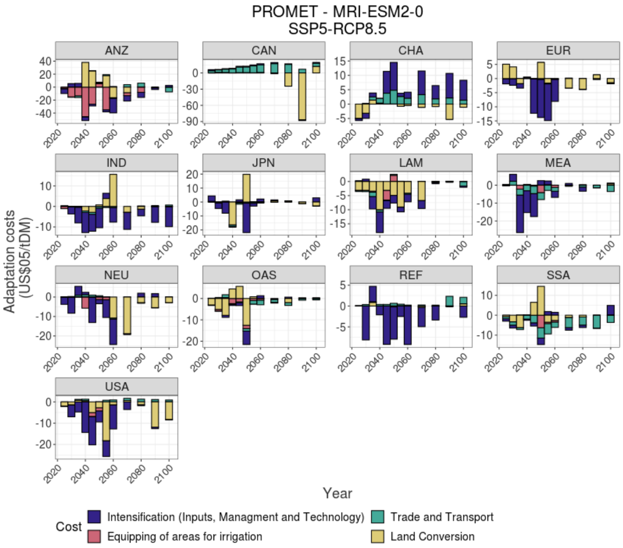


Supplementary Figure 10: Regional production in millions (mio.) of tonnes of dry matter (tDM) of crop and livestock in 2100 for SSP5- RCP8.5's most divergent scenarios (PROMET-MRI-ESM2-0 and CYGMA1p74-UKESM1-0-LL), and MAgPIE's default combination (LPJmL-MRI-ESM2-0), and the SSP5-NoCC scenario (same socio-economic trajectory but no climate impacts) The plot includes only the regional irrigated and rainfed production patterns of 4 staple crops (maize, rice, soybean, and temperate cereals).

Regional details of adaptation costs

a



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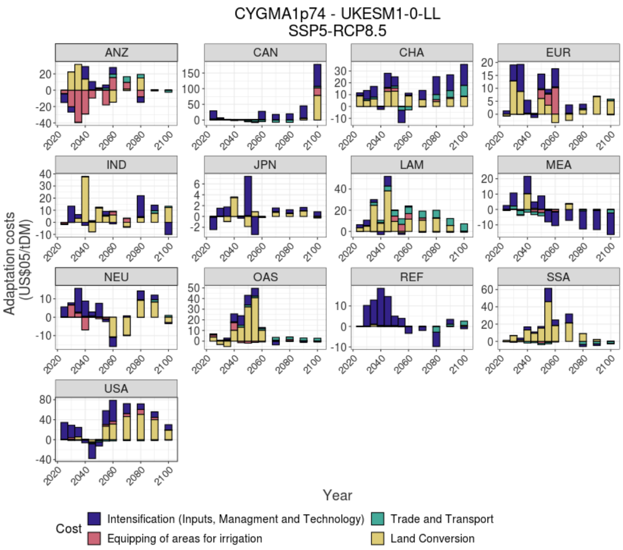

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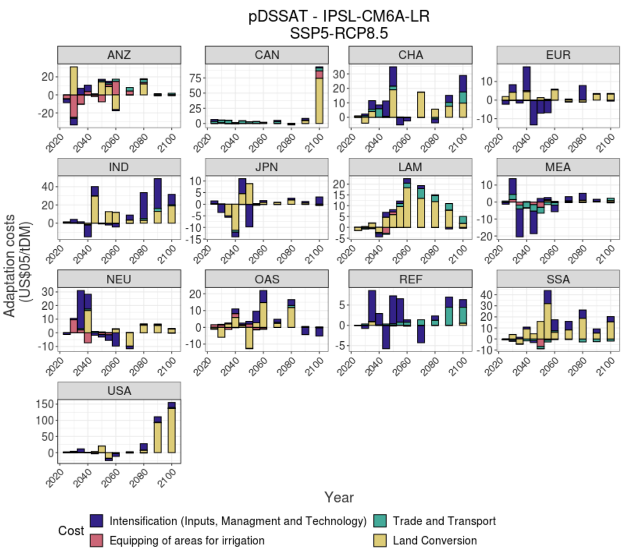
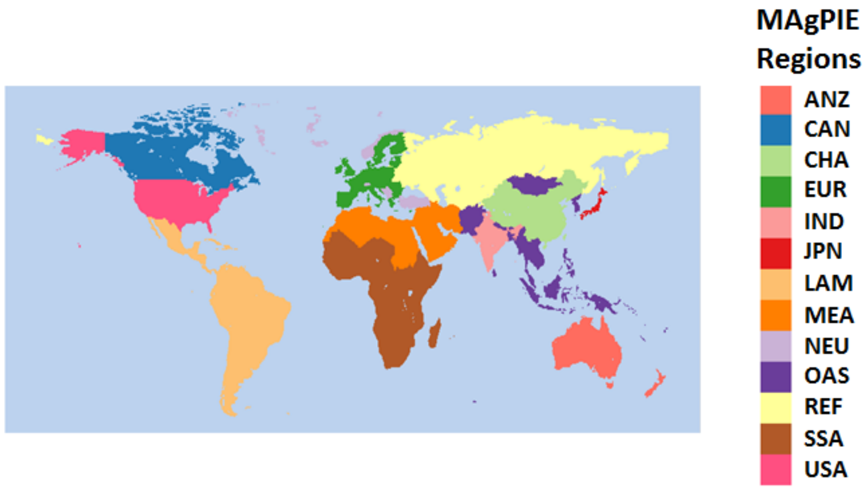


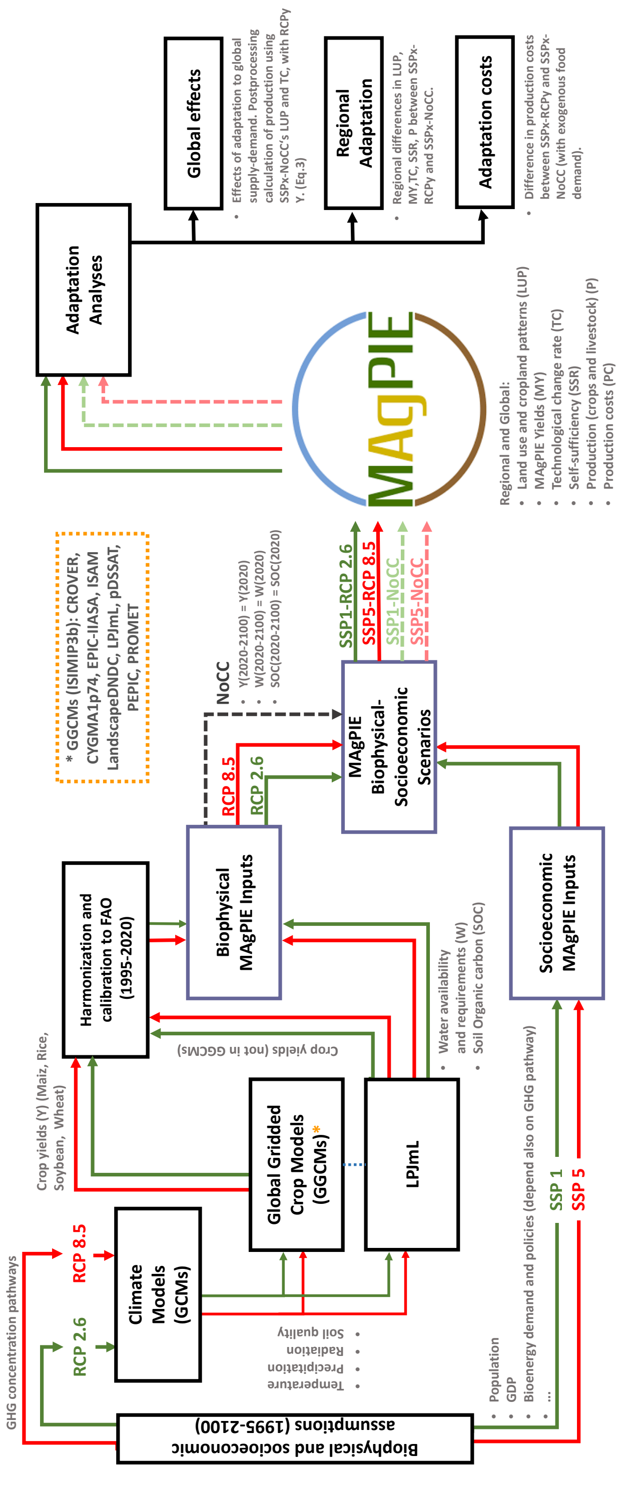
Supplementary Figure 11: Regional details of adaptation-related costs for crop production under SSP5-RCP8.5 for the GCMs-GGCMs at the extremes of the range of average projected impacts and the for the scenario with the highest adaptation costs. a) PROMET-MRI-ESM2-0 (most positive), b) CYGMA1p74-UKESM-LL (most negative), and c) the GCM-GGCM with the higher land-use adaptation costs

Socio-economic world regions used in MAgPIE



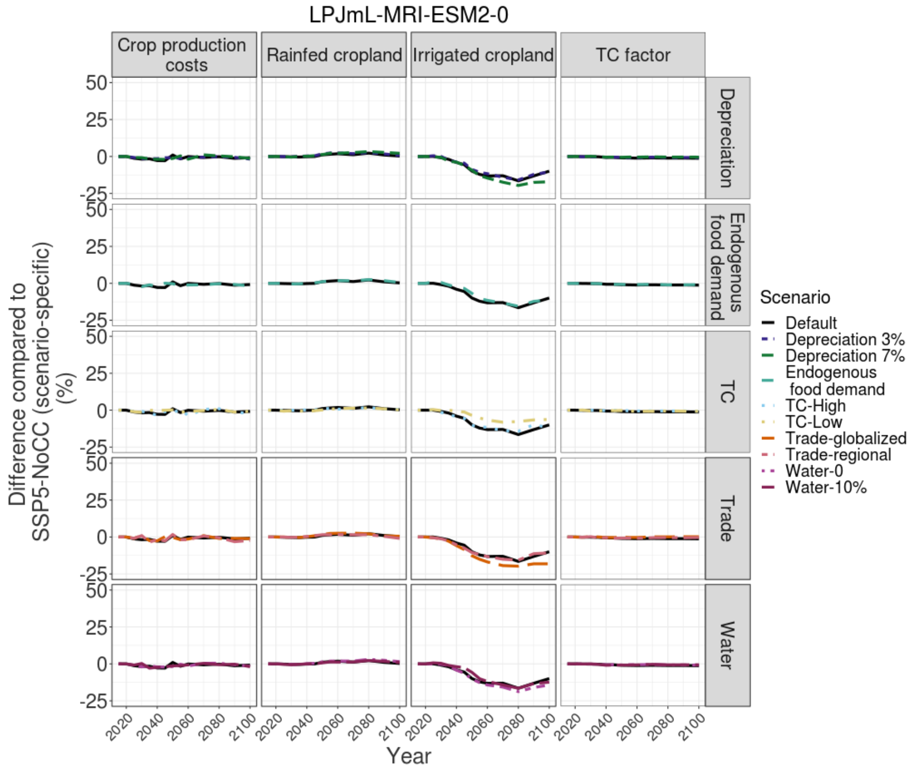
Supplementary Figure 12: **MAgPIE's economic world regions**. Australia and New Zealand (ANZ),Canada (CAN), China (CHA), European countries in the EU (EUR), India (IND), Japan (JPN), Latin America (LAM), Middle East and Northern Africa (MEA), European countries not in the EU (NEU), Other Asian countries (excluding China, India, Middle East, Japan and Reforming Economies) (OAS), Reforming economies that were part of the USSR (REF), Sub Saharan Africa (SSA), United States of America (USA)

Modeling protocol

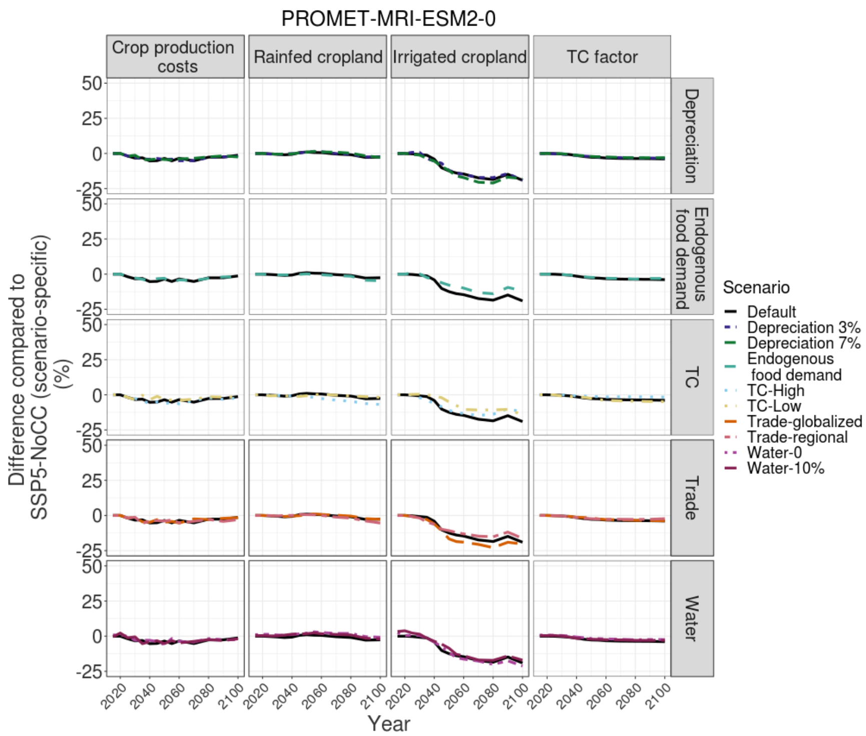


Supplementary Figure 13: **Modeling protocol and adaptation analyses**. The flow diagram depicts the modeling protocol, including data generation, used to build the assumptions and constraints in MAgPIE for the no climate (SSPx-NoCC), the high (SSP5-RCP8.5), and the low (SSP1-RCP2.6) emissions scenarios simulations. Black boxes represent processes, the purple the gathering of data (no calculation is done), and the orange box contains the information of crop models used to generate the impact data

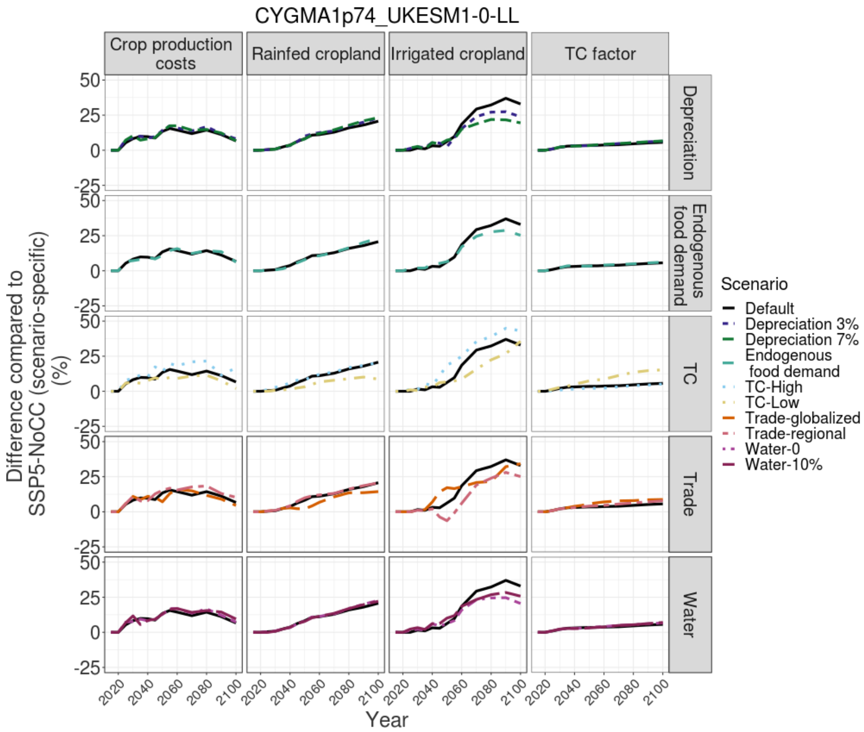
205 ## Sensitivity Analysis

206 

Supplementary Figure 14: Sensitivity analysis comparing the default run for LPJmL-MRI-ESM2-0 (SSP5-RCP8.5), the solid black line, and different scenarios including various changes in assumptions (depreciation of capital either 7% or 3%, available water saved for environmental reasons 0% and 10%), settings (endogenous food demand ON), or scenario interpretation (share of trade based on fixed self-sufficiencies and not in a free competitive market; regional=90%, and globalized=40%; and elasticity between R&D investments and technological change factor (TC), high=3.3, and low=1.5)

207 

Supplementary Figure 15: **Sensitivity analysis comparing the default run for PROMET-MRI-ESM2-0 (SSP5-RCP8.5), the solid black line, and different scenarios including various changes in assumptions (depreciation of capital either 7% or 3%, available water saved for environmental reasons 0% and 10%), settings (endogenous food demand ON), or scenario interpretation (share of trade based on fixed self-sufficiencies and not in a free competitive market; regional=90%, and globalized=40%; and elasticity between R&D investments and technological change factor (TC), high=3.3, and low=1.5**



Supplementary Figure 16: **Sensitivity analysis comparing the default run for CYGMA1p74-UKESM1-0-LL (SSP5-RCP8.5), the solid black line, and different scenarios including various changes in assumptions (depreciation of capital either 7% or 3%), settings (endogenous food demand ON), or scenario interpretation (share of trade based on fixed self-sufficiencies and not in a free competitive market; regional=90%, and globalized=40%; and elasticity between R&D investments and technological change factor (TC), high=3.3, and low=1.5; available water saved for environmental reasons 0% and 10%**

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