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Interrelations between the water, energy and food systems and climate change impacts in the Zambezi River Basin

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About the project

Southern Africa –Towards Inclusive Economic Development (SA-TIED)

SA-TIED is a unique collaboration between local and international research institutes and the government of South Africa. Its primary goal is to improve the interface between research and policy by producing cutting-edge research for inclusive growth and economic transformation in the southern African region. It is hoped that the SA-TIED programme will lead to greater institutional and individual capacities, improve database management and data analysis, and provide research outputs that assist in the formulation of evidence-based economic policy.

The collaboration is between the United Nations University World Institute for Development Economics Research (UNU-WIDER), the National Treasury of South Africa, the International Food Policy Research Institute (IFPRI), the Department of Monitoring, Planning, and Evaluation, the Department of Trade and Industry, South African Revenue Services, Trade and Industrial Policy Strategies, and other universities and institutes. It is funded by the National Treasury of South Africa, the Department of Trade and Industry of South Africa, the Delegation of the European Union to South Africa, IFPRI, and UNU-WIDER through the Institute's contributions from Finland, Sweden, and the United Kingdom to its research programme.

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ABSTRACT

The WHAT-IF model was applied to Southern Africa to investigate the impact of climate change and variability on water infrastructure investment planning for the Zambezi River Basin. Zambezi water investment decisions are linked with the climate change impacts on the regional rainfed agricultural system of Southern Africa and electric generating system of the Southern African Power Pool. Climate change will have significant impact on streamflow, rainfed crops and will impact hydropower production. To address the uncertainty about future climates we examine four emissions scenarios with 7,200 climates each while overlaying 100 spatially- and temporally consistent weathers for each climate, capturing the full range of both uncertainty and variability. Trade-offs between agriculture, hydropower and ecosystems are limited under the current climate. Assuming irrigation is developed, those trade-offs increase significantly with climate change. Enforcing more ecosystem conservation policies would principally affect hydropower production but could also affect irrigated agriculture under the driest climate change scenarios. Under severe climate change impacts, ignoring water needs for ecosystems could lead to underestimating water constraints for irrigation. Result show that considering the inter-annual climate variability is even more important than climate change trends. For the region, the effect of climate on crop yields and hydropower production in extreme years is much more than the effect in average years. This suggests the need to better account for such weather events in investment planning.

Keywords: Food Security, Climate Change Impacts, Hydroeconomic Modeling, Water-Energy-Food Nexus, Southern Africa, Sustainable Development.

1 INTRODUCTION

When considering the interrelations of food systems with water and energy systems single sector models are not advised, If climate change impacts are being considered it is even more important that an integrated modeling approach is needed. This study applies just such a model, the WHAT-IF nexus model (Payet-Burin et al., 2019) to the Zambezi River Basin (Payet-Burin and Strzepek, 2021) to gain insights into the impacts of future climate change and variability on the water, food, and energy systems of the riparian countries of the Zambezi River Basin. The objective of the study is to evaluate cross-sectorial impacts of climate change in the Zambezi River Basin: How will climate change affect water supply, hydropower production, energy prices, agriculture production, crop prices, and trade-offs between different sectors?

The study is organized as follows: Section 2 presents the WHAT-IF model. Then the Zambezi River Basin and the climate change scenarios are introduced. Section 5, Results and discussion, assesses the impact of climate change on the economic, power, and energy sector, and on trade-offs between them. Section 6 summarizes the findings and formulates recommendations.

2 THE WHAT-IF MODEL

WHAT-IF (Payet-Burin et al., 2019) is a hydroeconomic optimization model where the water, agriculture and power systems are represented within a holistic framework. All management decisions regarding water (e.g. storage, allocation), agriculture (e.g. area, crop, trade), and power (e.g. production, transfer, capacity investments) are optimized in order to maximize total welfare economic surplus. The model is based on a perfect foresight and perfect cooperation framework. This means that trade-offs are internally solved, and that one sector might forgo benefits to another in order to generate more benefits at the Basin level. Also, future conditions are known to the optimization framework, which leads to its anticipating wet and dry years.

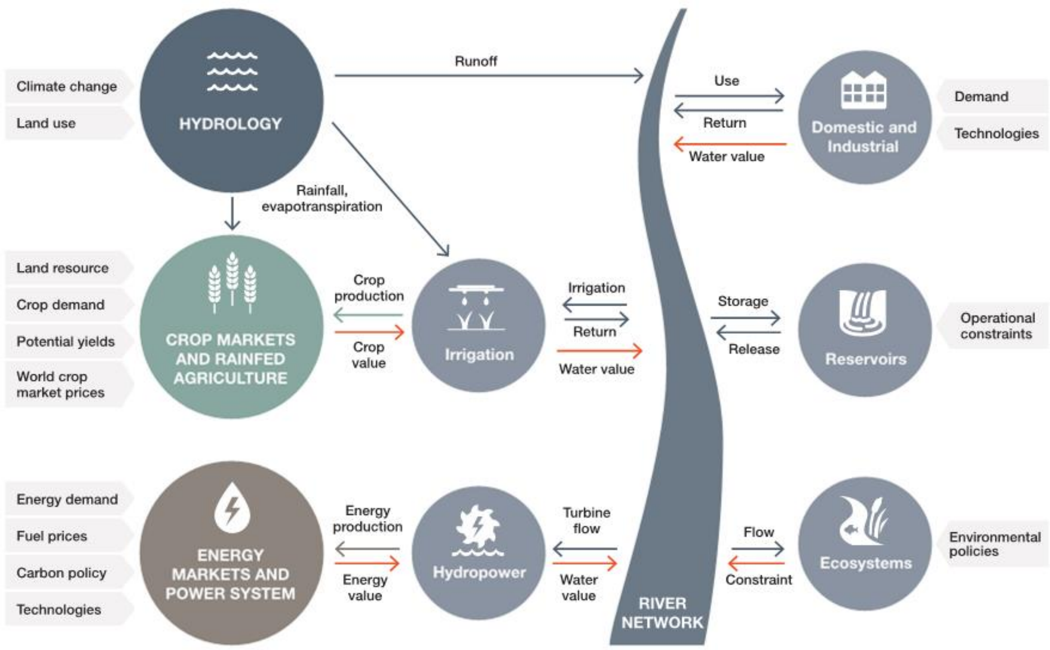

Figure 1: Conceptual representation of interrelations in the WHAT-IF model. The circles represent modules, arrows represent feed-back loops, and grey tags represent exogenous factors. All flows are holistically solved in order to maximize welfare economic surplus.

In WHAT-IF, the main link between the energy and agriculture sectors represented in the model is the use of water by hydropower production and for irrigated agriculture (Figure 1). Climate change impacts the hydrology, which in turns impacts the water resource and agriculture. Potential yields are an exogenous factor and are affected by hydrological conditions and water allocation by using the yield water response function from FAO Irrigation and Drainage Report 33 (Doorenbos & Kassam, 1979). Crop demand, own-price elasticity, available land, and world market prices are also exogenous factors. Trade of crops between crop markets is solved by the economic optimization framework based on transport costs the demand and supply of crops.

Payet-Burin and Strzepek (2021) present the application of WHAT-IF to the Zambezi: the data used and how the formulation of the water, energy and agriculture systems is represented in the model. This paper focuses on the analysis of potential climate changes on the Zambezi energy and agricultural sectors.

3 THE ZAMBEZI RIVER BASIN

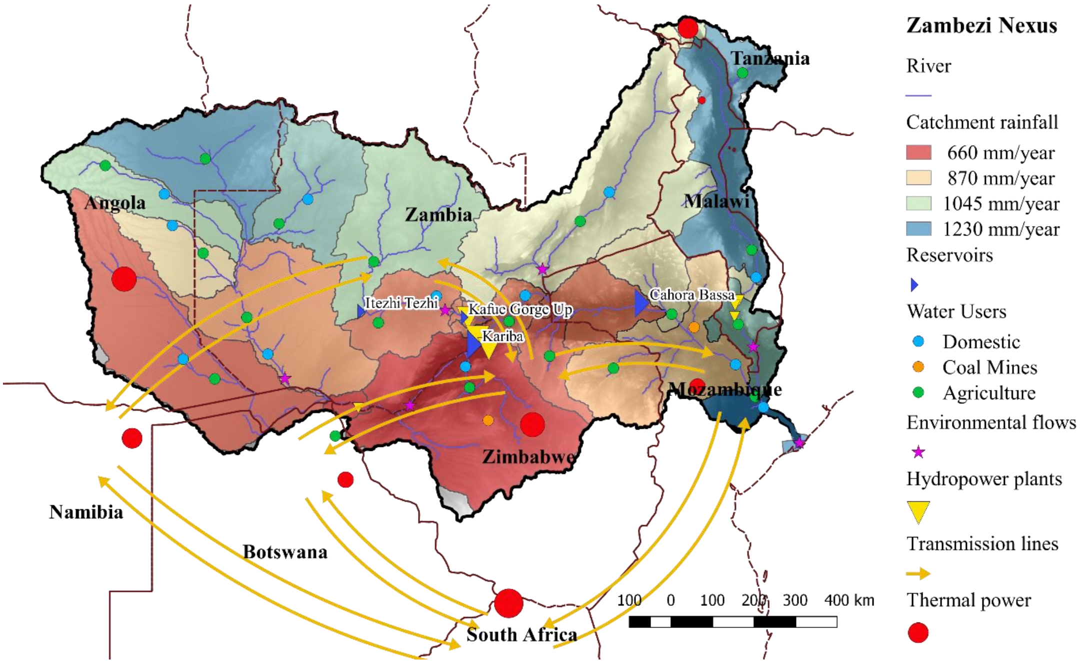

Figure 2: Conceptual representation of the Zambezi River Basin in the WHAT-IF model.

The Zambezi River Basin sustains more than 40 million people in eight riparian countries (Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe). The river is an essential resource supporting agriculture, hydropower, water supply and sanitation, industries, mining, fisheries, tourism, navigation and ecosystems. The dependent population is expected to grow to 70 million by 2050, which will increase the pressure on the water, energy, and food resources (SADC et al., 2015). The conceptual representation of the river basin in the WHAT-IF model is presented in Figure 2 (some aspects are not represented, such as crop markets).

4 THE UNCERTAIN FUTURE CLIMATE

4.1 Probabilistic projections of future climates

Here we consider future climate and weather, based on two emissions scenarios. The Paris forever (PF) scenario has atmospheric greenhouse gas (GHG) concentrations rising through the century. The other scenario, 2 degree C, has emissions reductions performing in such a way as to limit global warming to an increase of no more than 2 °C by 2100 (Schlosser et al. ,2020).

Paris forever: Countries meet the mitigation targets in their nationally determined contributions (NDCs) and continue to abide by them through the end of the century. The Paris Agreement includes NDCs submitted at the 2015 Paris Conference of the Parties (COP) of the Framework Convention on Climate Change (FCCC). These NDCs – aimed at the reduction of CO_2 and other GHG emissions – generally deepened and extended through 2030 the NDCs made at the 2009 Copenhagen COP through 2020. These reductions are typically expressed as (1) an absolute emissions target, measured as an annual level of emissions measured in Mt; (2) a percentage reduction from a pre-determined baseline, which can easily be converted into an absolute emissions target; or (3) an emissions intensity target, measured as emissions in relation to GDP.

2 degree C: This scenario aims to limit climate warming to no higher than a 2˚C global average by 2100. This is achieved by implementing a globally coordinated, smoothly rising carbon price – such that emissions are reduced. Variations in mitigation policies result in the overall uncertainty of different patterns of resource and energy use, different choices of technology, and drag on overall economic growth. This is also combined with the uncertainty of the global climate response that is represented in the Massachusetts Institute of Technology Earth System Model (MESM, Sokolov et al., 2019). As described in Reilly et al. (2018), these co-evolving uncertainties projected within a Latin-hypercube sampling result in an overall probability of achieving the target at 66%.

For each of the emissions scenarios, we use 7 200 climates, generated as described by Schlosser et al. (2020). Each of these climates show projected changes in monthly precipitation and near-surface average temperature from 2020 to 2069. These climates vary for many reasons including:

- imperfect human understanding of the global climate system;
- uncertainties in emissions paths, especially for the higher emissions scenario; and
- the inherent chaotic properties of the climate system (and climate models), which imply that small perturbations can lead to drastically different outcomes over time, especially at relatively fine spatial scales.

4.2 Adding climate variability

For each of the climates, we consider 100 different weather realizations, each spanning a 50-year period. The weather realizations are random draws of the detrended monthly time series from the Princeton Global Forcing database from 1948 to 2016 (Sheffield, Goteti, and Wood 2006).

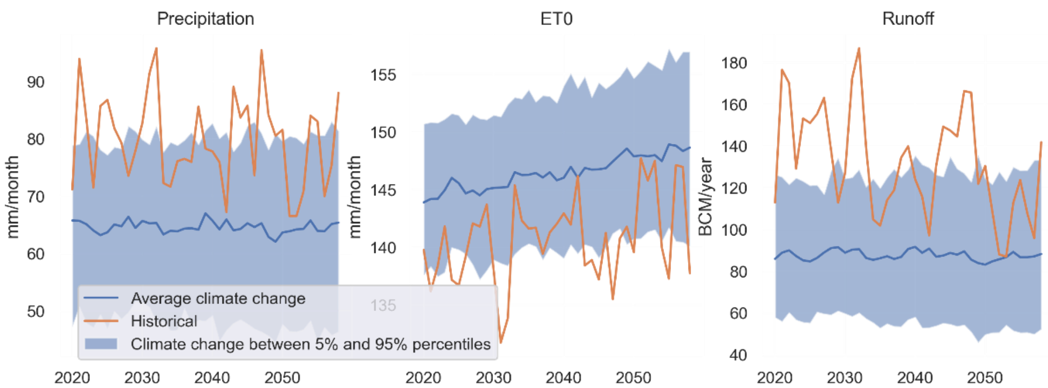

Figure 3: Climate change projections (Paris forever scenario) for the Zambezi River Basin. The historical time series is a repeat of the observed hydrology between 1960 and 2000.

On average, climate change scenarios point towards a decrease in average precipitation, with high variability among scenarios (Figures 3–6). As a result, a similar trend is observed for runoff, with the climate scenarios varying between -60% and +10% runoff on average over the period 2020–2060. As all climate projections point towards an increase of temperature, the average potential evapotranspiration is found to increase for all scenarios. Runoff decreases at a greater rate than precipitation decreases due to the increase in evapotranspiration.

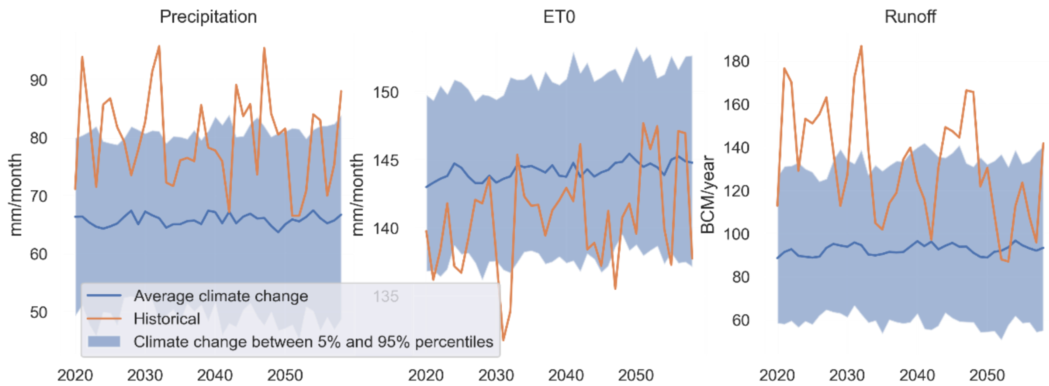

Figure 4: Climate change projections (2 degree C scenario) for the Zambezi River Basin. The historical time series is a repeat of the observed hydrology between 1960 and 2000.

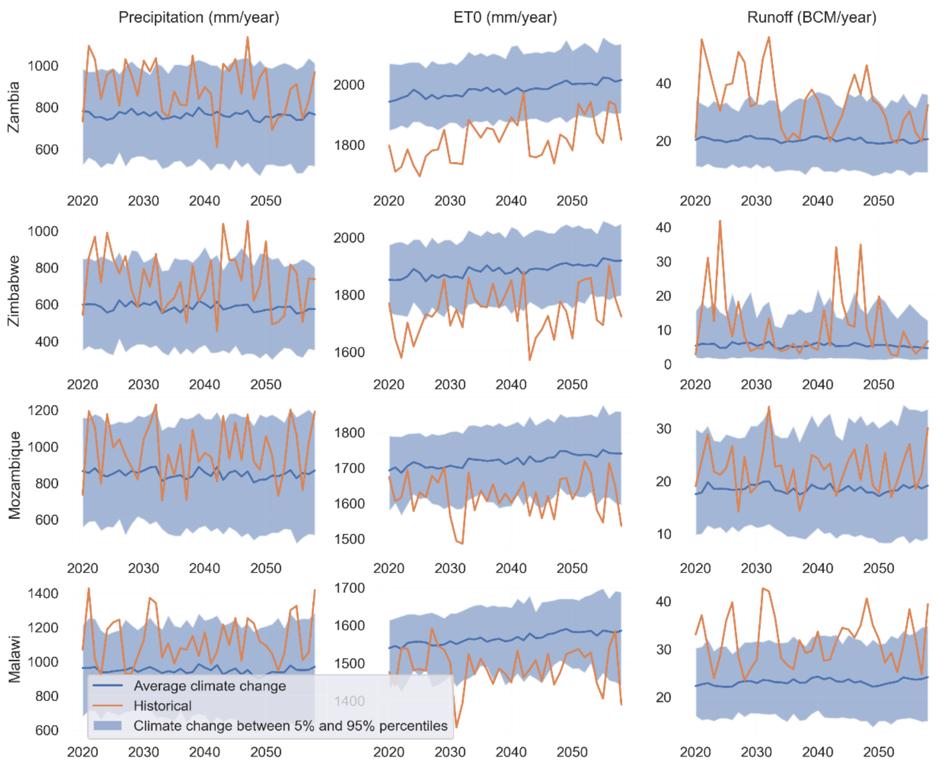

Figure 5: Climate change projections (Paris forever scenario) for the major riparian countries of the Zambezi River Basin. The historical time series is a repeat of the observed hydrology between 1960 and 2000.

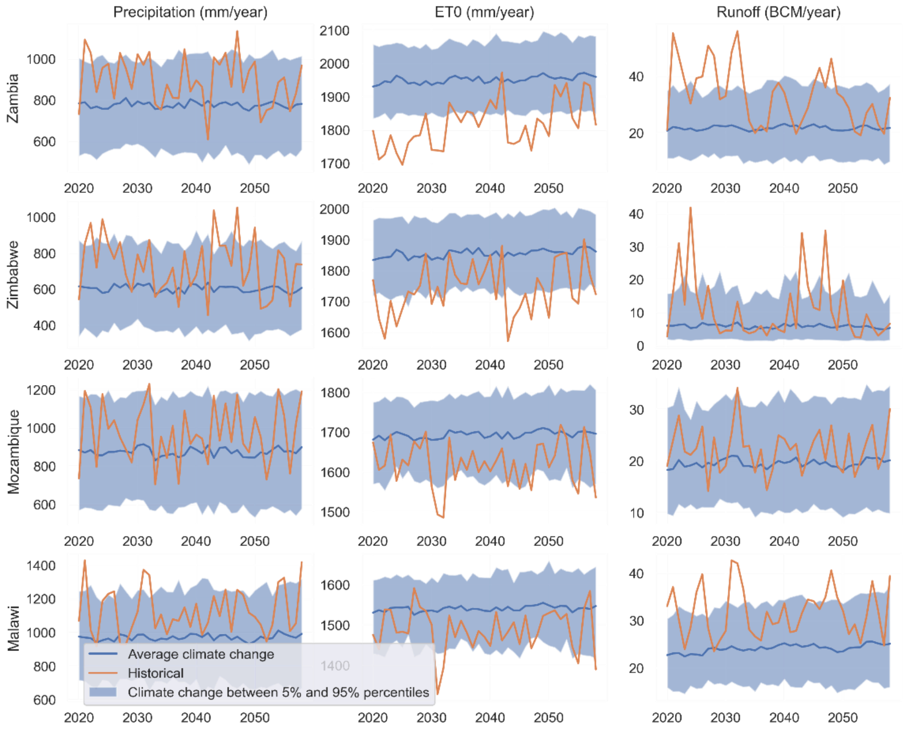

Figure 6: Climate change projections (2 degree C scenario) for the major riparian countries of the Zambezi River Basin. The historical time series is a repeat of the observed hydrology between 1960 and 2000.

5 RESULTS AND DISCUSSION

5.1 Economic impacts

Throughout the analysis, the climate change scenarios are compared to the historical (observed) hydrology from 1960 to 2000, considering the same projected socio-economic context for the period 2020–2060. Impacts on the energy system, which are related to hydropower production, are found to be almost linearly proportional to the relative change in runoff (

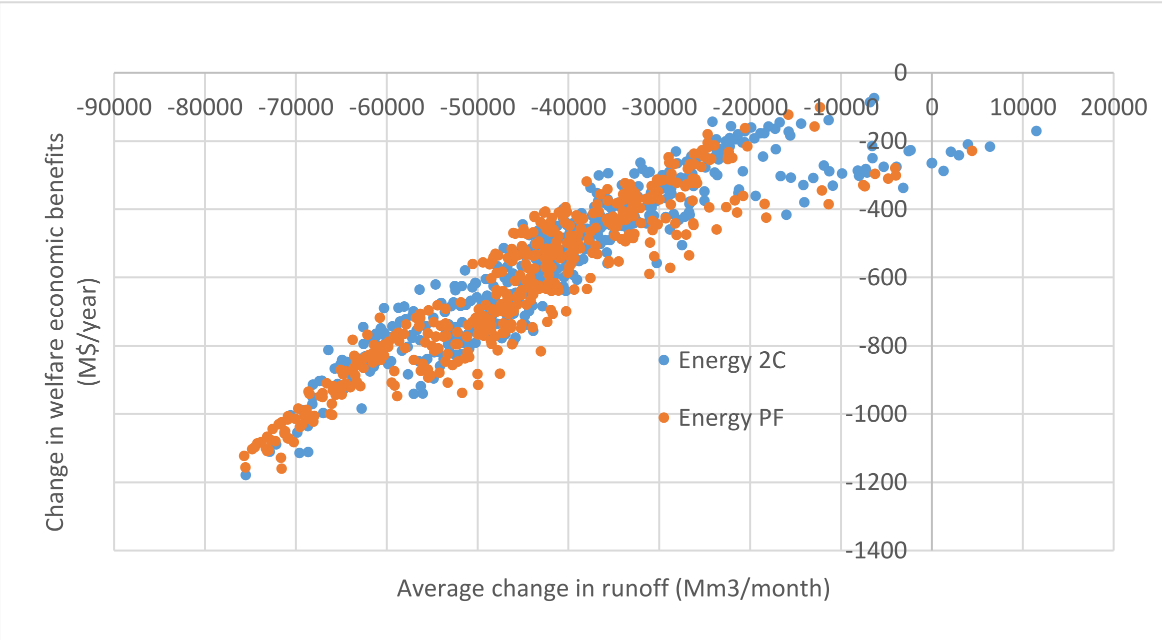

Figure 7). The median impact on hydropower production is -29% and -33% of current production for the PF and 2C scenarios respectively, but extremely dry scenarios could lead to a reduction of up to 60% of hydropower production over the period 2020–2060 (**Error! Reference source not found.**). This is comparable with Cervigni et al. (2015), who found that hydropower production could decline by up to 60 % in the driest climate change scenario.

Impacts on the agriculture system shows a non-linear relationship to relative change in runoff (Figure 9), as precipitation and evapotranspiration also play an important role in affecting rainfed crops. Rainfed crops represent most of the crop production and agriculture benefits in Southern Africa.

All climate scenarios increase the demand for irrigation, as temperature – and thus evapotranspiration – increases in all climate change scenarios. However, under extreme drying the increase in demand is not met, leading to a reduction in irrigation water consumption and economic benefits of irrigation.

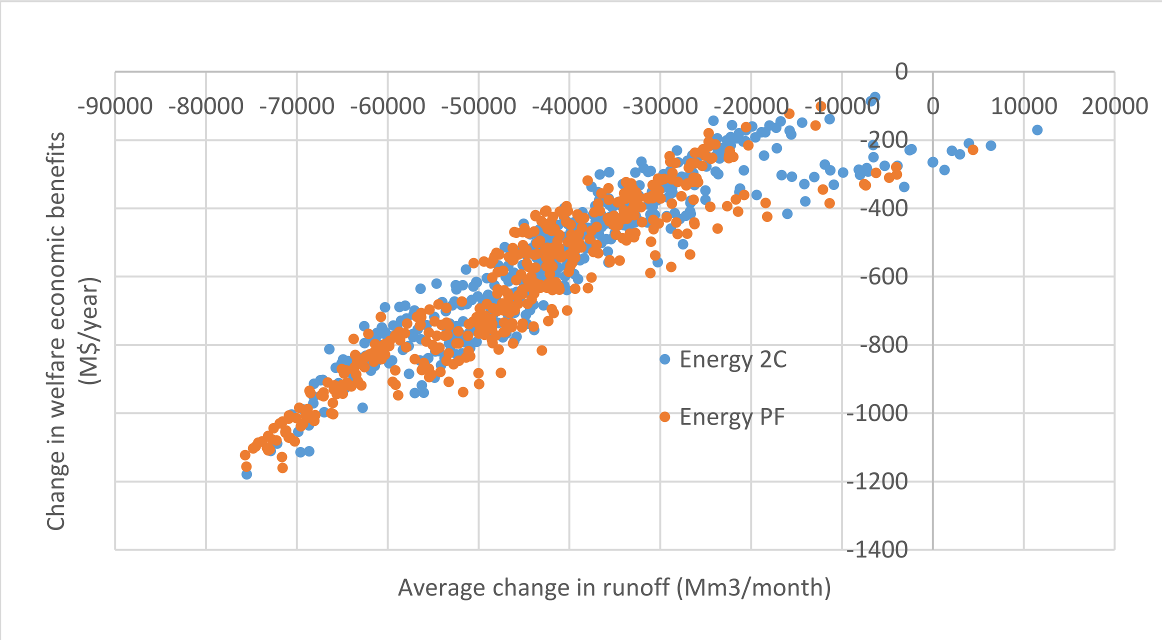

Figure 7: Energy impacts of climate change. Values are different welfare economic benefits of the energy sector between historic (observed) hydrology time series versus projected Paris Forever and 2 degree C climate-impacted time series for the total welfare surplus, averaged for the period 2020–2060. Each dot represents a climate change scenario timeseries.

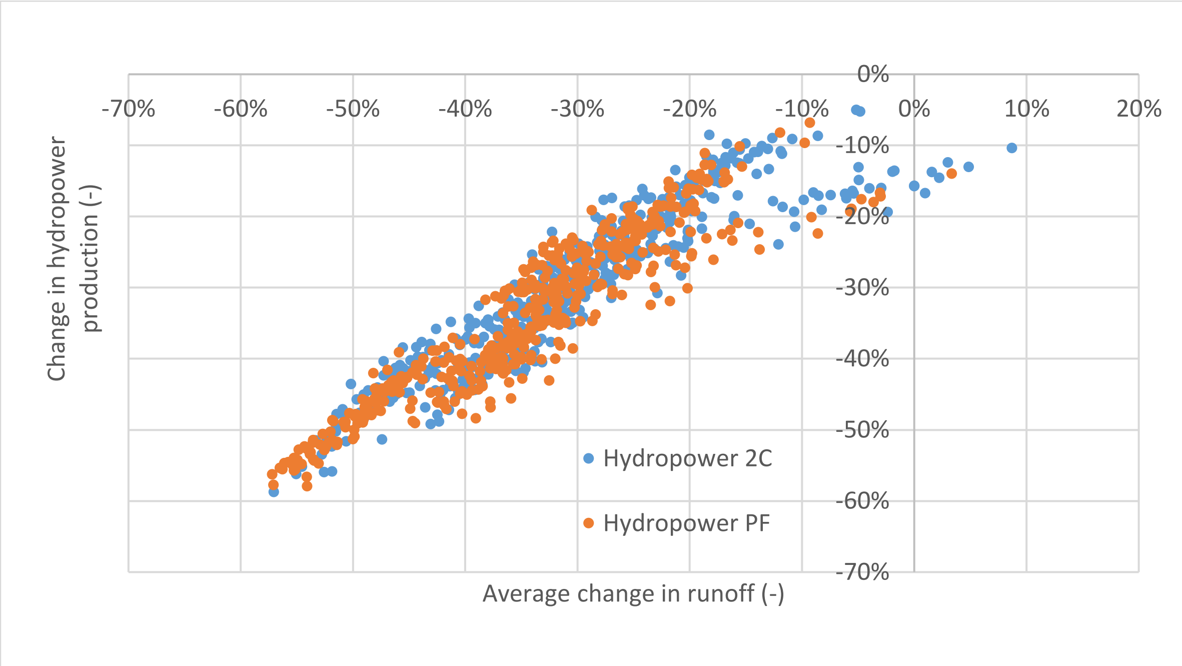

Figure 8: Hydropower impacts of climate change. Values are difference in hydropower production between historic (observed) hydrology time series versus projected Paris Forever and 2 degree C climate-impacted time series for the total hydropower production, averaged for the period 2020–2060. Each dot represents a climate change scenario timeseries.

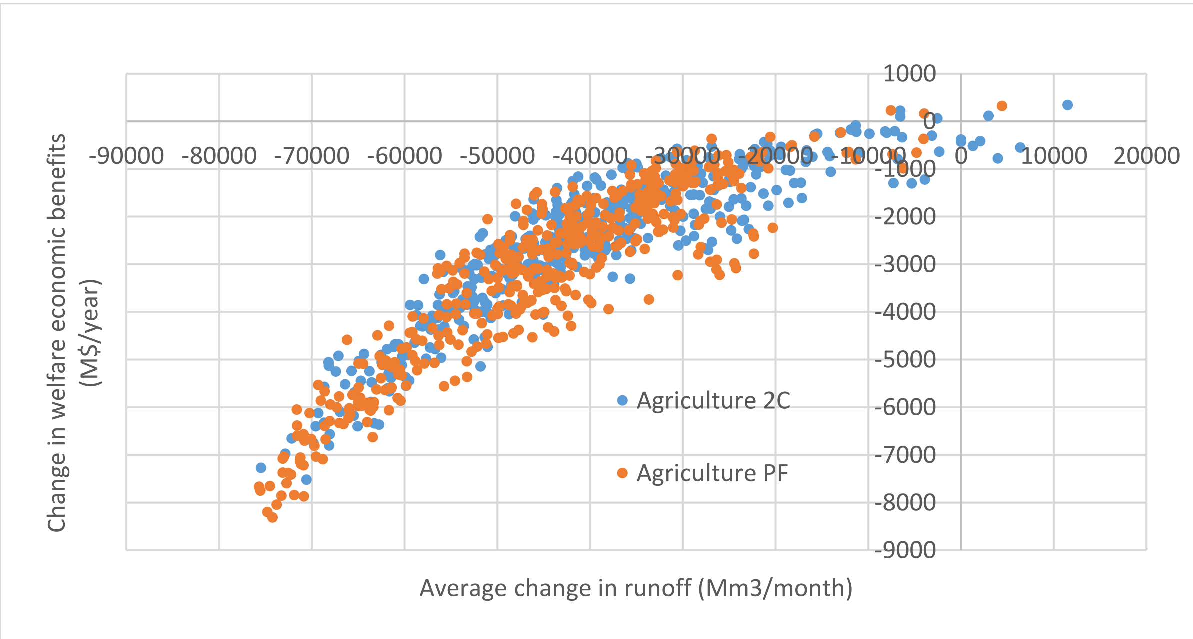

Figure 9: Agricultural impacts of climate change. Values are different welfare economic benefits of the agriculture sector between historic (observed) hydrology time series versus projected Paris Forever and 2 degree C climate-impacted time series for the total welfare surplus, averaged for the period 2020–2060. Each dot represents a climate change scenario timeseries.

The variability of potential climate impacts starts to be particularly important at the horizon 2030–2050 (Figures 10 and 11). The figures show three interesting results: 1) the wide range of uncertainty in economic performance that grows with time; 2) the decrease in hydropower value is much less than the decrease in hydropower production, based on the increasing value of low-carbon energy; and 3) the value of irrigation crops increases by over 200% across forty years. The average value of irrigated crop production for the driest climate change scenario in the 2050 decade is at the level of the average value across climate change scenarios in the 2040 decade, showing that the driest climate scenario has a similar effect to delaying agricultural development by 10 years.

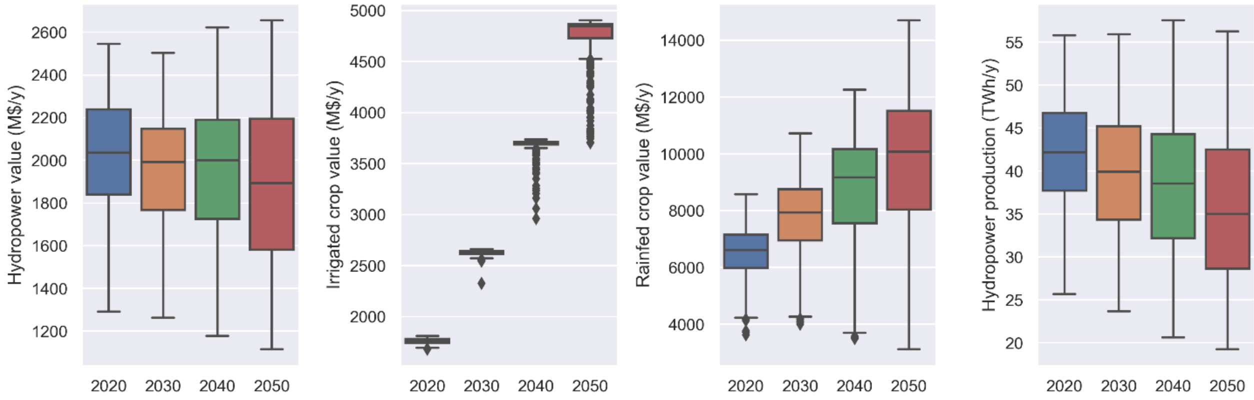

Figure 10: Climate change impacts on hydropower and crop production from the Paris Forever scenario. Values are the projected climate-impacted time series, averaged over the decades 2020 to 2050. Each box represents the quartiles Q1 to Q3, each bar represents the median (Q2), each top whisker the highest datapoint within Q3+1.5*(Q3-Q1), and dots are values beyond this.

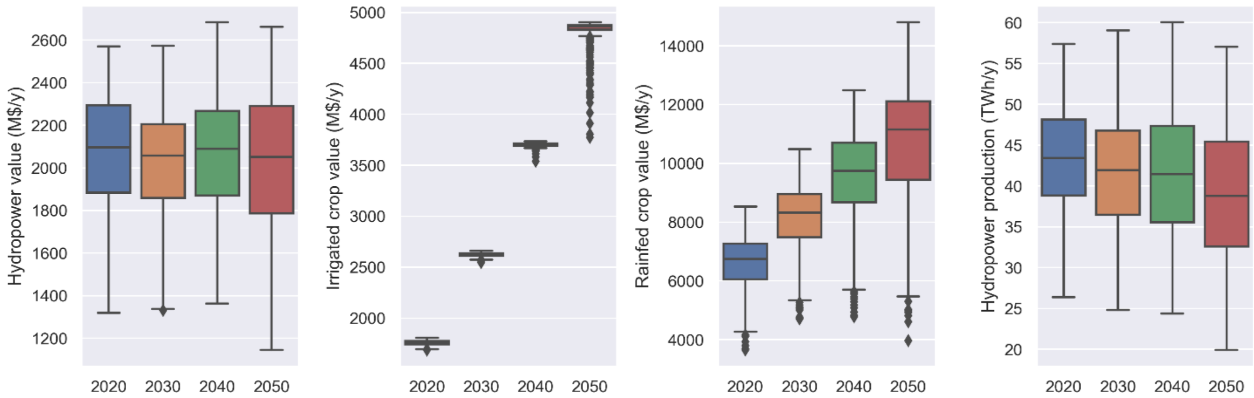

Figure 11: Climate change impacts on hydropower and crop production from the 2 degree C scenario. Values are the projected climate-impacted time series, averaged over the decades 2020 to 2050. Each box represents the quartiles Q1 to Q3, each bar represents the median (Q2), each top whisker the highest datapoint within Q3+1.5*(Q3-Q1). and dots are values beyond this.

5.2 Impacts on the energy system

In all countries the average trend is towards decreasing hydropower production (Figures 12 and 13).

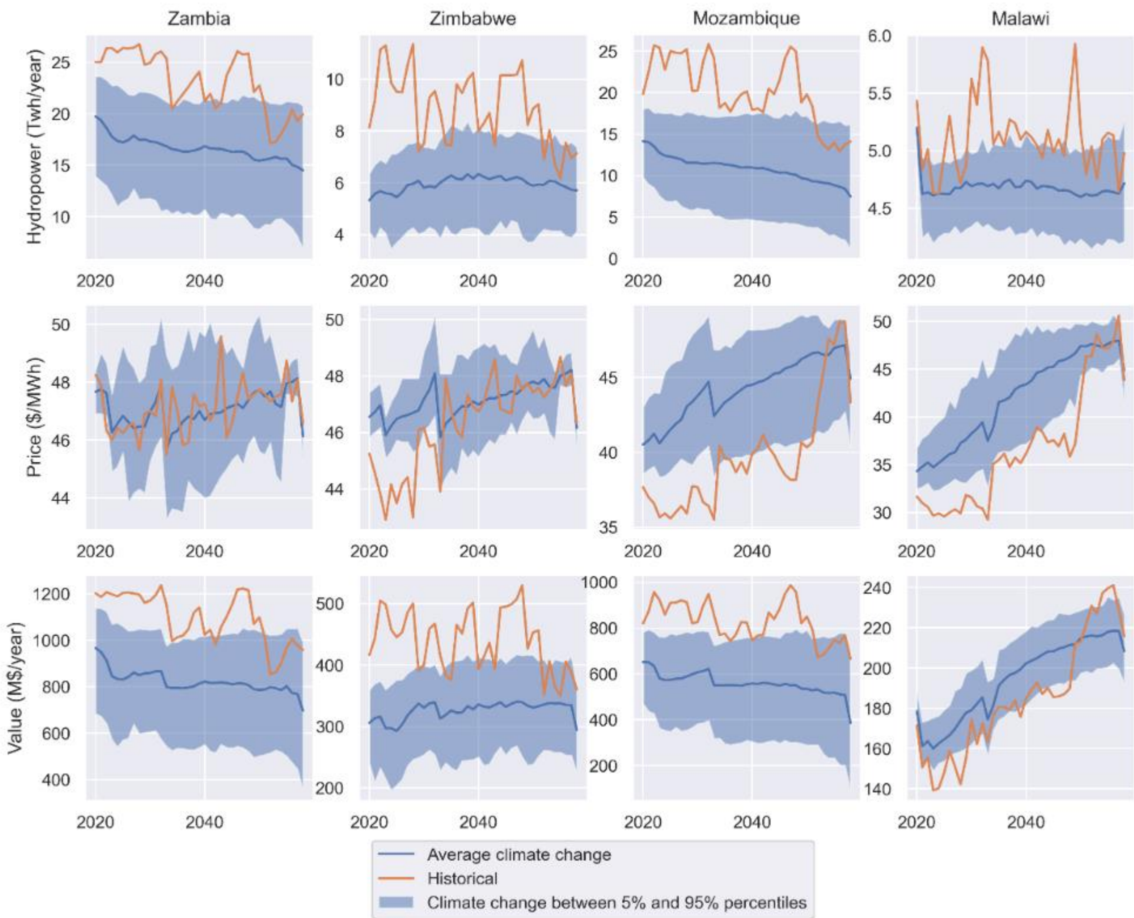

Figure 12: Climate change impacts on hydropower production from the Paris forever scenario. "Historical" refers to the historical climate projected in the future socio-economic conditions.

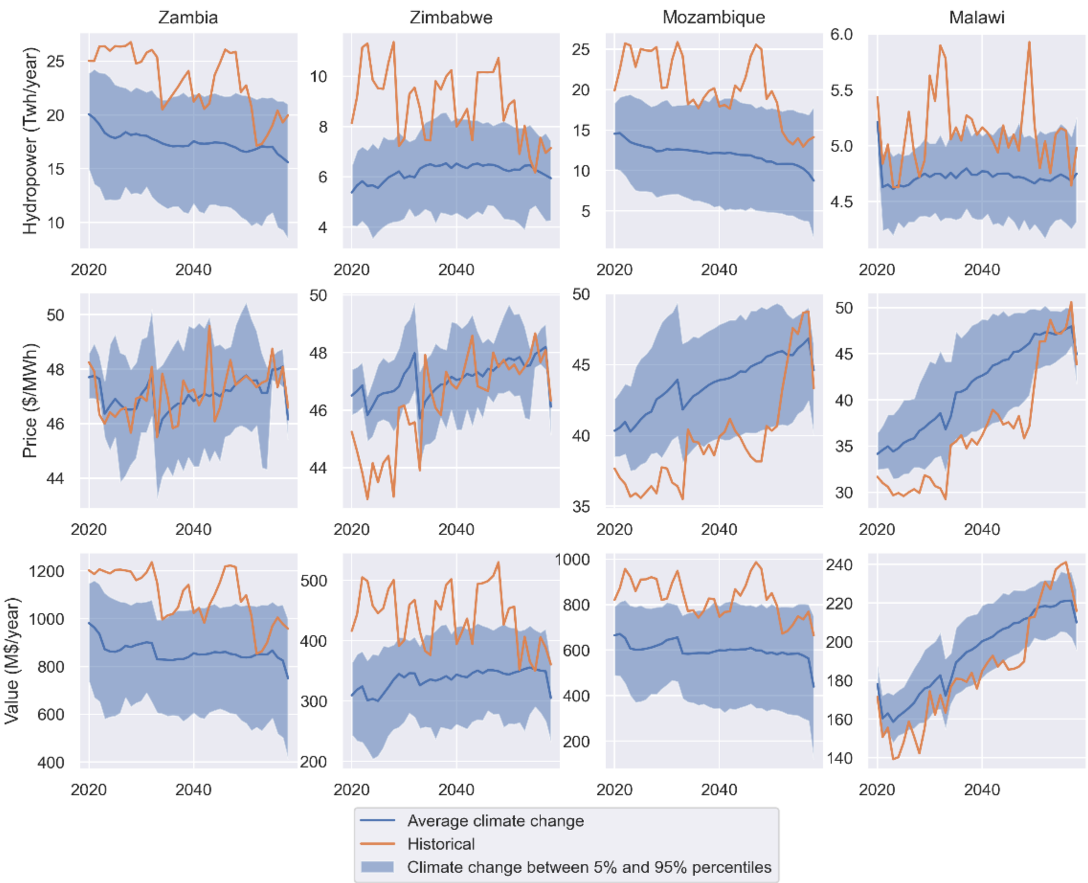

Figure 9: 2C Climate change impacts on hydropower production from the 2 degree C scenario . "Historical" refers to the historical climate projected in the future socio-economic conditions.

Mozambique, the most downstream country, is most affected, with an average reduction of 45%, while Malawi is the least affected, with an average decrease of less than 10% (**Error! Not a valid bookmark self-reference.**). The upstream reservoir of Mozambique, Cahora Bassa, can store more than half of the current total Zambezi yearly runoff and thus compensate for dry periods. However, the hydropower plant is already not using its full capacity, so the reduction in runoff leads to a reduction in hydropower production. In Malawi, with the development of new hydropower plants, the energy demand could be almost fully supplied by hydropower. Thus, climate change has an important impact on the power price, which could vary between +10 to +30% compared to in the historical climate. This is in line with Spalding-Fecher et al. (2017), who found that decrease in hydropower production could increase power generation costs by up to 30% in the Zambezi countries. On average, impacts for the PF scenario are found to be more important than for the 2C scenario, but the main difference is across individual projections.

Table 1: Average climate change impacts on hydropower. Values for the 2 degree C (2C) and Paris forever (PF) scenarios are the average values across climate scenarios.

Hydropower	Scenario	Zambia	Zimbabwe	Mozambique	Malawi
Production	Historical	23.2	8.9	20.2	5.1
(TWh/year)	2C	17.5	6.2	12.0	4.7
	PF	16.6	6.0	10.9	4.7
Market value	Historical	1 096	439	830	185
($\$X10^6$/year)	2C	860	336	600	194
	PF	821	326	558	194
Price ($/MWh)	Historical	47.3	49.4	41.1	36.2
	2C	49.2	54.4	49.9	41.0
	PF	49.4	54.7	51.4	41.5

5.3 Impacts on the agriculture system

Climate change impacts on the area, production, yield and price of main crops are compared to the historical hydrology (with future socio-economic conditions) in the WHAT-IF model and the IFPRI Global Food Trade model IMPACT. Climate change increases the variability of the production of crops (Figures 14 and 15), which leads to lower yields and production, on average (Table 2).

Table 2: Average climate change impacts on maize production. Values for the 2 degree C (2C) and Paris forever (PF) scenarios are the average value across climate scenarios.

Maize	Scenario	Zambia	Zimbabwe	Mozambique	Malawi
Production	Historical	1 836	1 514	985	3 149
(1000 t/year)	IMPACT	1 922	2 002	563	2 052
	2C	1 561	777	788	2 583
	PF	1 502	718	748	2 472
Harvested area	Historical	703	822	721	1 729
(1000 ha/year)	IMPACT	714	859	722	1 733
	2C	690	715	694	1 673
	PF	684	697	687	1 661
Yield (t/ha)	Historical	2.6	1.8	1.4	1.8
	IMPACT	2.7	2.3	0.8	1.2
	2C	2.3	1.1	1.1	1.5
	PF	2.2	1.0	1.1	1.5
Price ($/t)	Historical	286	182	110	286
	IMPACT	281	281	281	281
	2C	286	257	176	286
	PF	286	261	186	286

Zimbabwe is the most affected country, with maize yields dropping by 50% on average across climate change scenarios (Table 2). In the IMPACT model, the inter-annual variability of water resources is not represented, so we can see important differences also with the historical climate. Crop prices oscillate between the export and import prices, depending on the level of the production. When comparing rainfed agriculture (e.g. maize is mostly rainfed) and irrigated agriculture (e.g. cereals are mostly irrigated), climate change is observed to principally impact the former. Irrigated crops can compensate for the increase in crop water demand by allocating more surface water, as long as surface water constraints do not limit irrigation. On average, impacts for the PF scenarios are found to be more important than those for the 2C scenarios, but the main difference is across individual projections.

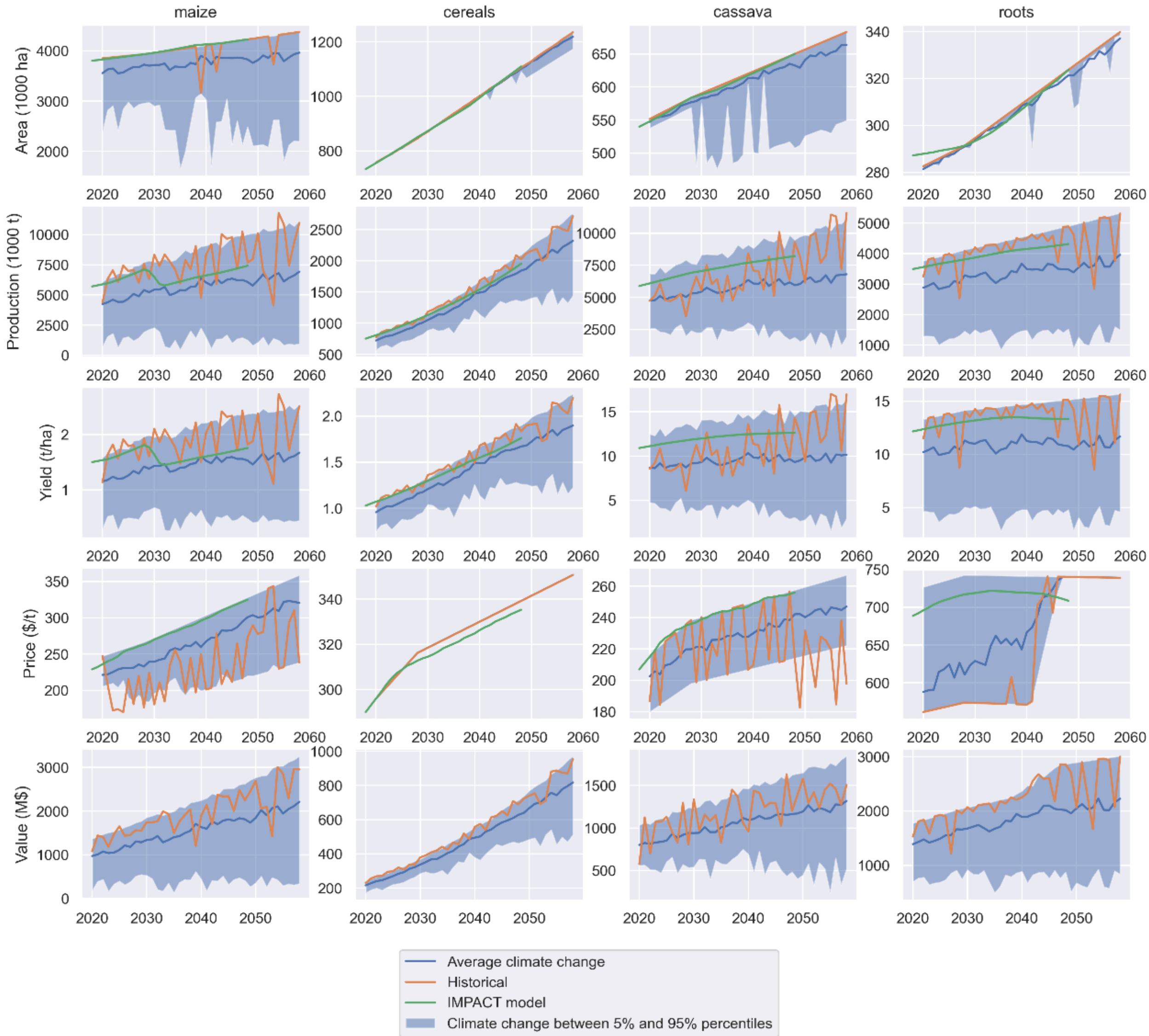

Figure 10: Paris forever scenario climate change impacts on the main crops. "Historical" refers to the historical climate projected into future socio-economic conditions.

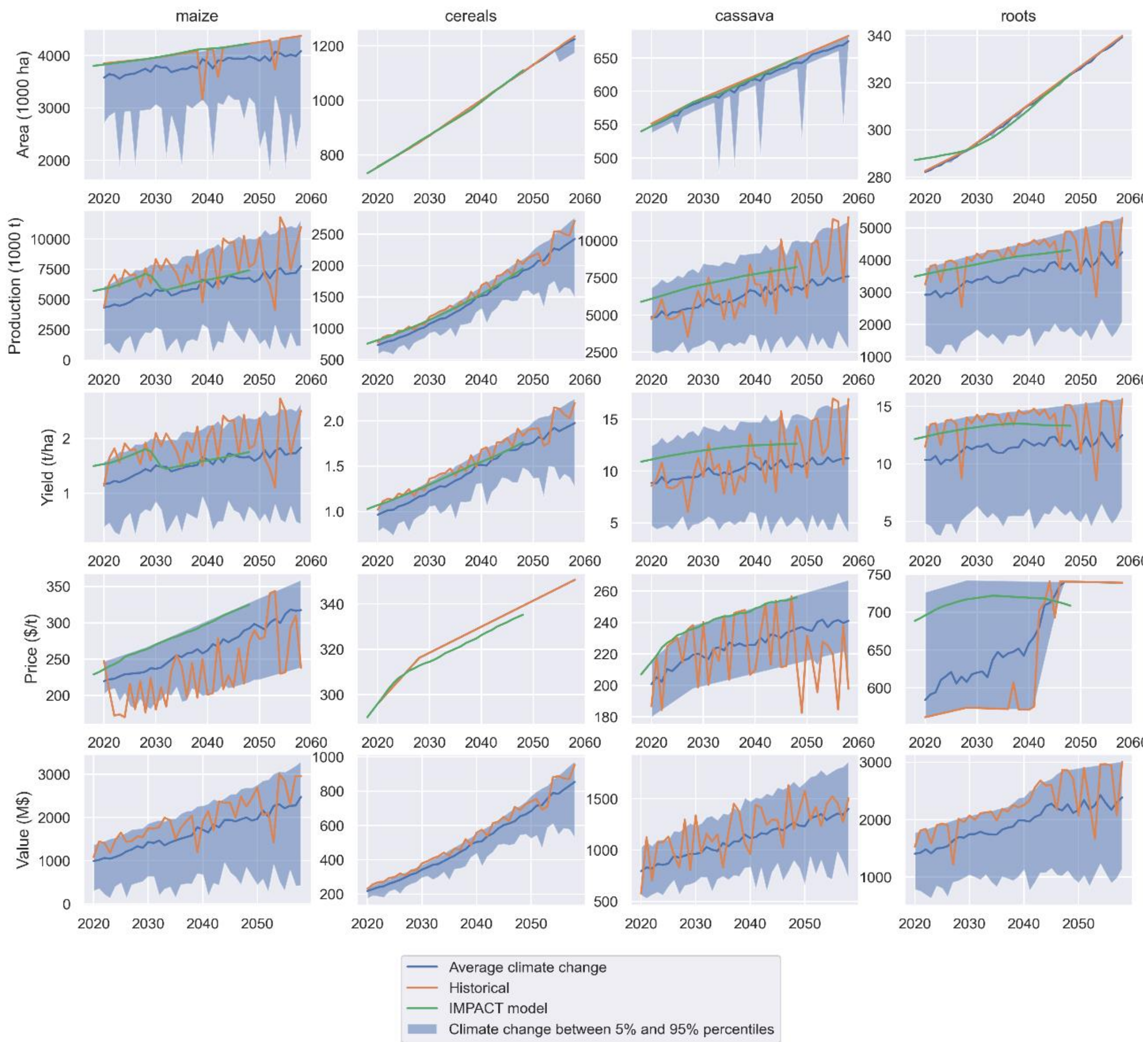

Figure 15: 2 degree C scenario climate change impacts on the main crops. “Historical” refers to the historical climate projected into future socio-economic conditions.

5.4 Impacts of the inter-annual variability of the hydrological parameters

For this analysis the World Bank study *Enhancing the climate resilience of Africa’s infrastructure* (Cervigni, et al 2015) was used. The bias-corrected climate projections for the African continent employed a total of 121 projections through 2050; 56 are GCMs from the CMIP3 ensemble, and 65 are from the CMIP5 archive using the Princeton hydroclimatic data as the historical baseline (Sheffield, Goteti, and Wood 2006). This provides for a single ensemble of climates that represents both model and emission scenario uncertainty.

The impact of not considering the inter-annual variability of the hydrological parameters (runoff, precipitation and evapotranspiration) was evaluated. To do this, the climate change analysis was performed, but using the 10-year rolling average of the climate change projection time series. For example, the precipitation in January 2020 of a given climate change projection is computed as the average of all January months between 2015 and 2025. This results in deleting dry and wet years and exhibits only average climate change impacts (Figure 16).

We compared the impact on the agricultural system of using the full time series of the climate projections and the rolling average time series ignoring the inter-annual variability (Figure 17).

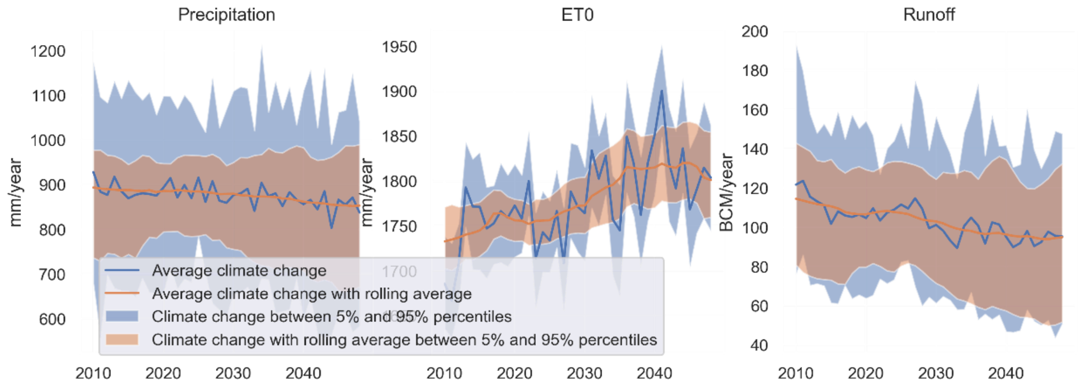

Figure 16: Climate change projections with and without rolling average.

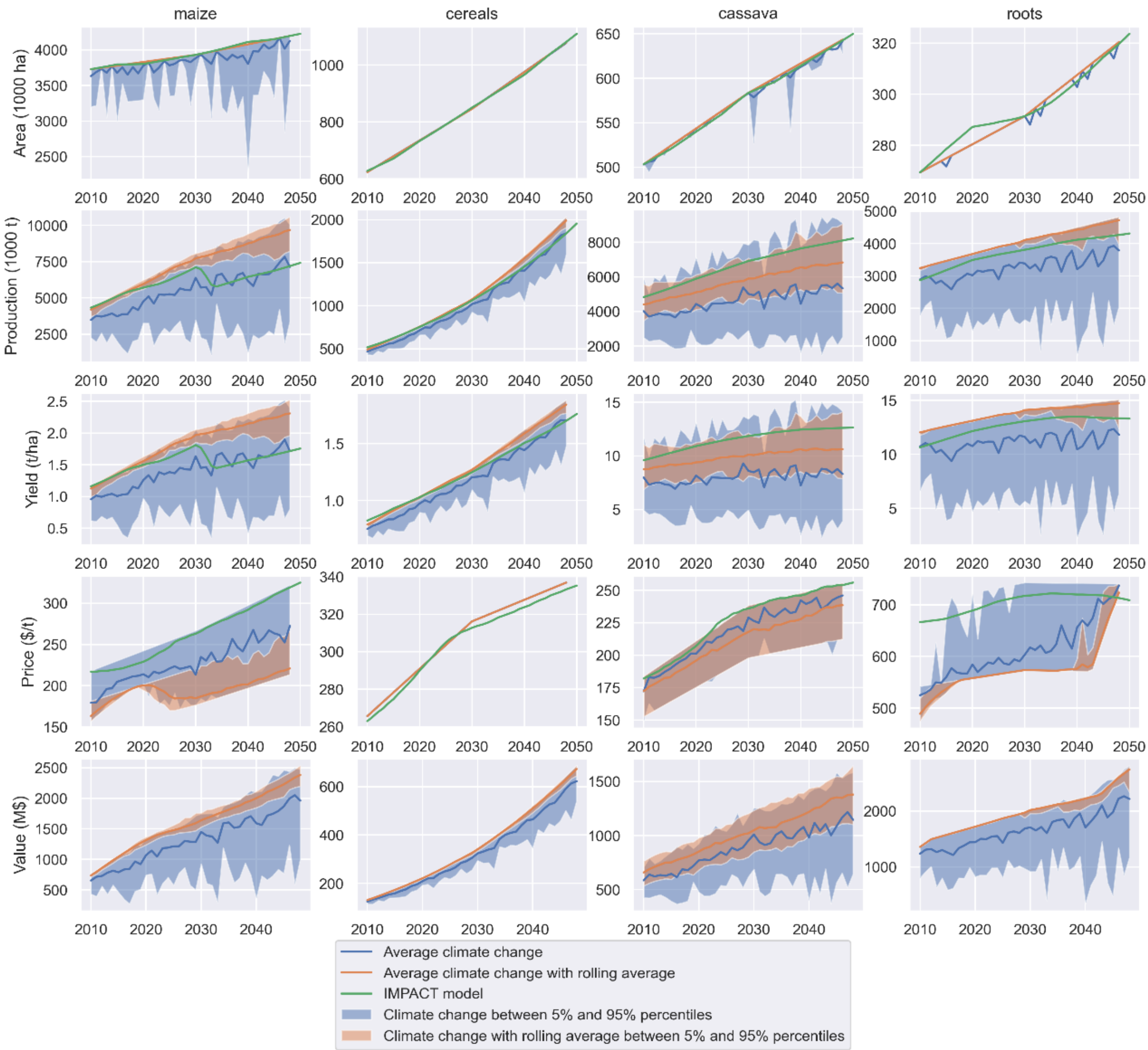

Figure 17: Climate change impacts on the agriculture system with and without rolling average.

It was observed that the averaged projections lead to considerably more stable yields and production of crops. The average production and yield through climate change projections are also higher. This is because, when considering the inter-annual variability, wet years do not compensate for dry years, as additional precipitation does not lead to additional yield beyond the optimal crop water demand. For example, when considering the inter-annual variability, the yield for cassava varies between 5 and 14 t/ha in the 2040 decade through scenarios, with an average of 8 t/ha. When using the averaged projections ignoring inter-annual variability, the yield is found to vary between 8 and 14 t/ha with an average of 11 t/ha. Thus, ignoring the inter-annual variability leads to overestimate the average cassava yield by around 30%, and the minimum value by around 80%.

This analysis shows that considering average conditions and ignoring the inter-annual variability of the hydrological parameters can lead to considerably overestimating yields and crop production, as it underestimates water constraints. The inter-annual variability effect is found to be as important, if not more so, than the average impact of climate change.

When carrying the same analysis for the power system, hydropower production is almost not affected, when using the averaged projections. This is because most hydropower production in the Zambezi is supported by large reservoirs, which can compensate for the inter-annual variability of runoff.

5.5 Impacts on the trade-offs between food, energy, and ecosystems

The trade-offs between the agriculture, energy, and ecosystems are considered by evaluating the impact of prioritizing one system over another for the different climate change scenarios. The reference solution is the allocation of water maximizing total economic welfare. The value of water to ecosystems is not represented, but prioritizing ecosystems is represented by introducing an environmental flow policy forcing the release of 7000 m^3/s in February, as evaluated in the MSIOA study (World Bank, 2010). Figure 18 shows the relative impact on key indicators of prioritizing one system against the optimal welfare economic solution for different climate change scenarios.

Prioritizing the agriculture system leads to little trade-off with the power system compared to the economically optimal solution, as it reduces hydropower production by less than 2% for the driest climate change scenarios in 2040. It also generates very few benefits to the agriculture system, as in the most extreme scenario water consumption is increased by 3%, increasing the irrigated crop value by 0.3%. This shows that the welfare economic optimal allocation of water is already in favour of irrigation (assuming irrigation schemes already exist, neglecting the cost of irrigation development). However, it does not mean that developing irrigation does not affect hydropower production. In Payet-Burin et al. (2019), developing irrigation schemes is found to negatively impact hydropower production, and the forgone hydropower production represents up to 10% of the irrigation development value in the driest climate change scenario.

In contrast, prioritizing the power system leads to mild increase in the hydropower production (up to +12%), but a strong decrease in irrigated agriculture (up to -60%) compared to the welfare economic optimal allocation of water. Here only the most extreme cases are presented (maximizing agriculture production and maximizing hydropower production) and not the entire Pareto front. Trade-offs mainly concern upstream agriculture (e.g. Kafue Flats, Kariba) forgoing benefits to downstream hydropower plants (e.g. Kafue Gorge, Kariba, Cahora and Mphanda Nkuwa). Potential trade-offs increase with time, as demand for water increases and climate change impacts become more severe.

Prioritizing ecosystems mainly leads to trade-offs with hydropower production, particularly when combined with climate change impacts (up to -12% hydropower production). Under almost all climate change scenarios, trade-offs with irrigation are limited, as irrigated crop value would be reduced by up to 5%. However, in the most extreme climate change scenarios, prioritizing ecosystems could lead to important trade-offs with irrigated agriculture, reducing its value by up to 50%. This shows that, in the coming decades, environmental flow policies are compatible with irrigation expansion while generating mild trade-offs with hydropower production. However, within a few decades, if climate change is towards the driest scenarios, there might be important trade-offs between ecosystems, irrigation, and hydropower.

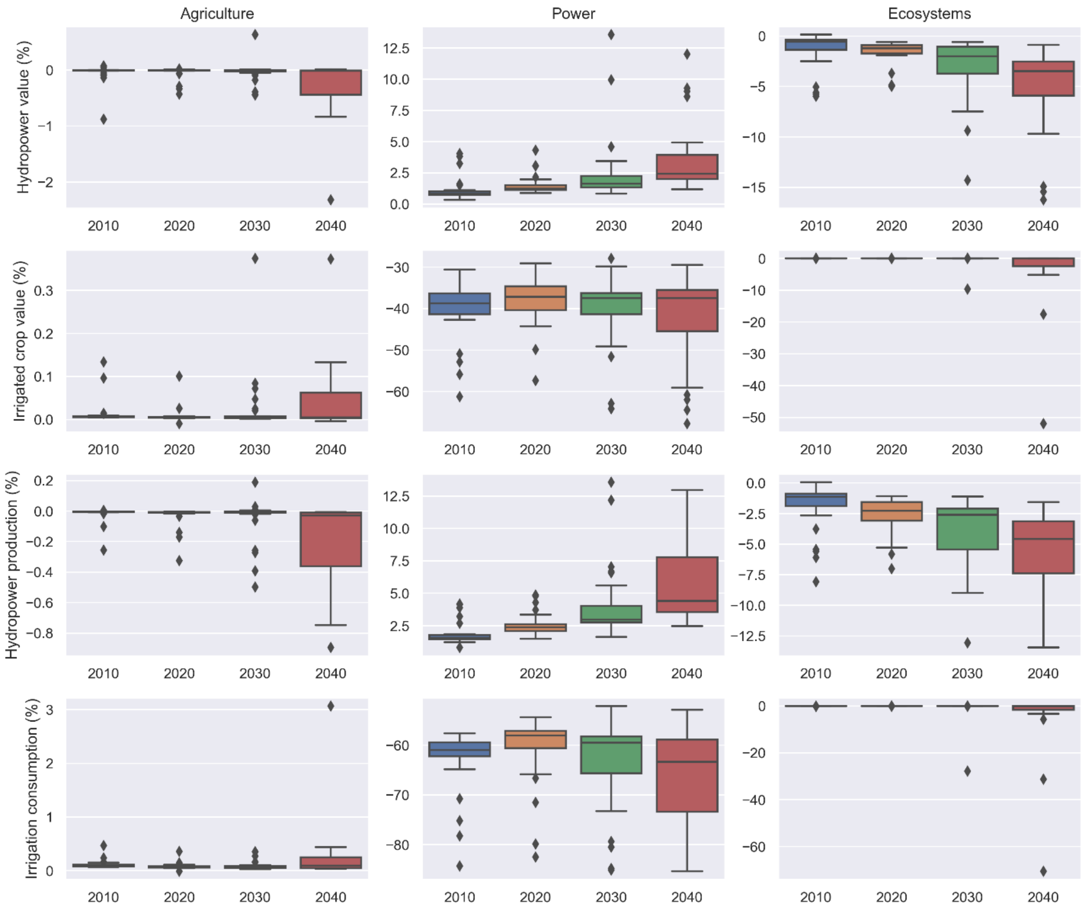

Figure 18: Trade-offs between hydropower, irrigation and ecosystems. Each column represents a different sector being prioritized in the objective function (agriculture, power, ecosystems), and the indicators show the difference with the economically optimal solution across climate change scenarios. The boxes represent the quartiles Q1 to Q3, the bars represent the median (Q2), the top whiskers the highest datapoint within Q3+1.5*(Q3-Q1), and dots are values beyond this.

6 CONCLUSIONS

The WHAT-IF model was applied to the Zambezi River Basin to assess how climate change might impact the water, energy and agriculture systems and their interrelations.

Climate change will have significant impact on rainfed crops. An increase in temperature increases crop water demand (and hence irrigation demand) in all scenarios, including those leading to more rainfall. In the most extreme climate change scenarios, the increase in irrigation demand cannot be satisfied (or is not economically viable), leading to a decrease in allocated water for irrigation.

Climate change will impact hydropower production: the average tendency is to decrease, with high variability among climate change scenarios (from -60% to -5% compared to historical climate).

On average, impacts for the Paris forever scenario are found slightly more important than for the 2 degree C scenario, but the main difference is across individual projections.

Trade-offs between agriculture, hydropower and ecosystems are limited under the current climate. Assuming irrigation is developed, the optimal welfare economic allocation of water is almost the same as prioritizing irrigation. Fully allocating water to hydropower would increase production by less than 5% in most scenarios, showing that in general there are little trade-offs between irrigation and hydropower.

For all cases, it can be seen that those trade-offs increase significantly with climate change. Enforcing more ecosystem conservation policies would principally affect hydropower production but could also affect irrigated agriculture under the driest climate change scenarios.

As important as climate change impacts are, to consider the inter-annual climate variability is even more important. Irrigated agriculture might be limited by surface water constraints only in the driest climate change scenarios. In the case of the Zambezi, representing surface water constraints for irrigated agriculture by ignoring the other sectors would lead to only little bias in the analysis, despite the impact of climate change and the potential evolution of the hydropower management. However, under severe climate change impacts and conservative ecosystem preservation policies, ignoring water needs for ecosystems could lead to underestimating water constraints for irrigation.

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