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Impacts of Climate Change on Water Availability and Crop Yield in Germany

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Abstract: Under a warmer climate, crop growth and crop yield could be affected by many factors (e.g. increasing temperatures, CO_2 fertilization and lower water supply) either positively or negatively. The present study aims in a) projecting the future water availability and low flow conditions in the five largest river basins in Germany, b) investigating the impact of climate change and CO_2 fertilization on crop yield, and c) studying the potential of having two yields (e.g. winter wheat – summer barley) per year under a warmer climate. The eco-hydrological model SWIM (Soil and Water Integrated Model) was driven by four regional climate models (CCLM, REMO, STAR and Wettreg) to simulate daily river discharge and crop yield in five large river basins in Germany. The impact on crop yield was studied for the basins Ems and Elbe with the STAR scenario. When evaluating climate impacts, an adjustment of net photosynthesis to higher CO_2 concentrations and a flexible crop rotation scheme based on the harvest index were used. As simulations show, until the middle of this century water discharge in all the studied rivers would be 8-30% lower in summer and autumn compared to the period 1961-1990. The current 50-year low flow is likely to occur more frequently in western, southern and part of central Germany, especially at the end of this century. Winter wheat yield is likely to decrease by about 6-10% under the STAR scenario due to lower water availability. However, CO_2 fertilization may compensate this negative effect and increase the crop yield by 9-14%. Besides, it is likely to have two yields (winter wheat-summer barley) per year in the Ems catchment after year 2030.

***Keywords**:* Climate change, water availability, crop yield, Germany.

1 Introduction

Under a warmer climate, crop growth and crop yield could be affected by many factors (e.g. increasing temperatures, CO_2 fertilization and lower water supply) either positively or negatively [Ainsworth and Long, 2005, Chmielewski and Potts, 1995]. Water availability in summer months is already a crucial factor affecting the agricultural yield in Germany, and it could become even stronger in future. For example, the 2003 drought damaged German agriculture to the tune of around 1.3 billion Euros [Munich Re, 2009]. However, the benefits from increase in temperature and CO_2 concentration for the growth of crops have also been observed in the recent years. In 2008, two grain harvests within one year have been recorded in Germany for the first time in history [TAZ, 2008]. Hence, great interest appeared recently related to changing climate, water resources and crop yield: would there be higher water stress in Germany and how would crop yield be influenced? Would crop yield be influenced by CO_2 fertilization? To which extent will it be possible to have two yields per year in Germany?

In order to better understand the interaction processes influencing crop yield, the eco-hydrological model SWIM (Soil and Water Integrated Model) was applied to simulate river discharge and crop yield in the five large river basins (Danube, Elbe, Ems, Rhine and Weser) in Germany. Besides the interaction between temperature, water and crop growth simulated in SWIM, the model includes an adjustment of net photosynthesis to higher CO_2 concentration and a flexible crop rotation scheme (harvesting time is not prescribed but depends on harvest index). The climate scenarios from four climate downscaling models (STAR, REMO, CCLM and Wettreg) were applied to run the input data for SWIM after the model validation. Taking into account the performance of different climate models in hydrological impact studies by Bronstert *et al.* [2007], the SWIM outputs driven by the STAR scenario were used for evaluating changes in the mean seasonal runoff and crop yield. The projected daily discharges driven by other RCM scenarios were used for low flow analysis. Based on this model system, the present paper aims a) to project the future water availability and low flow conditions, b) to investigate the impact of climate and CO_2 fertilization on winter wheat yield (the dominant crop in Germany), and c) to study the potential option of having two yields per year (winter wheat-summer barley) in Germany.

2 Study Area

Germany is located in Central Europe with a total area of 357,021 km^2. From the Northwest to the East and Southeast, the maritime climate gradually changes into a more continental climate. The German territory consists of five large river basins (the Elbe, upper Danube, Rhine, Weser and Ems), three medium-scale basins in the coastal area (Elder, Schlei/Trave and Warnow/Peene), and small parts of the Oder and Maas basins. The study area (Fig. 1a) is comprised of the five large basins, which cover about 90% of the whole German territory and include parts of neighbouring countries (Austria, Czech Republik, France, Switzerland etc). Fig. 1b shows the location of 30 selected gauge stations, which were used for assessing river discharge at the main rivers and large tributaries. The basins Ems and Elbe were chosen to study the climate impact on crops in the maritime climate (the Ems) and in the more continental climate (the Elbe).

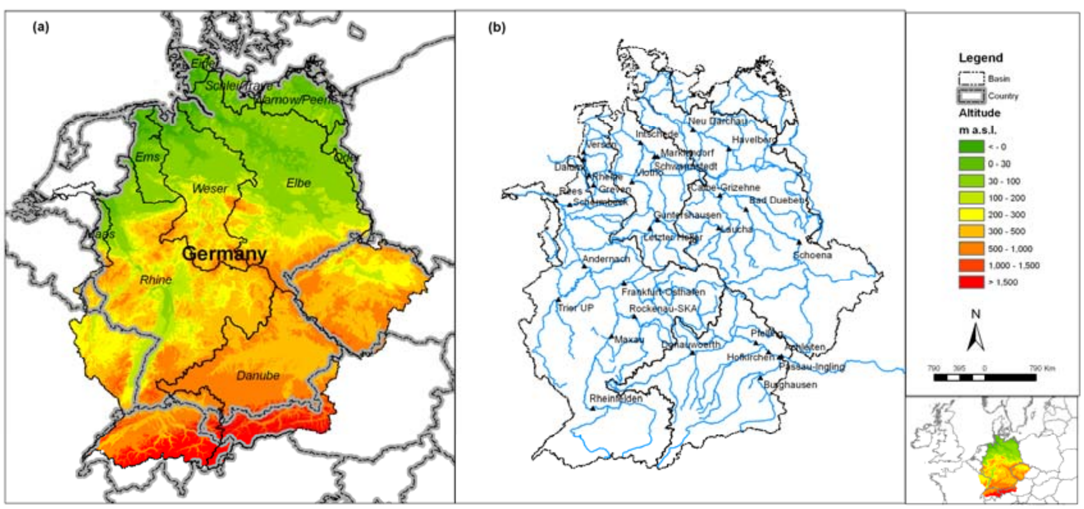

Figure 1 Digital Elevation Map of the study area and the river basins across Germany with locations of the selected gauge stations.

3 Methods

3.1 Climate Downscaling Models

There are different sets of regional climate projections for Germany, produced by both dynamical downscaling models, such as REMO [Jacob, 2001] and CCLM [Böhm *et al.*, 2008] and by statistical downscaling techniques such as WettReg [Enke *et al.*, 2005a, 2005b], and STAR [Orlowsky *et al.*, 2008]. Some general characteristics of each downscaling model are listed in Table 1.

Table 1 Characteristics of the climate downscaling models used in the study.

Model	Model type	Simulation period	GCM based	Emission scenario	Spatial resolution	Realization per scenario
CCLM	Dynamic	1960-2100	ECHAM5	A1B, B1	0.2°	2
REMO	Dynamic	1951-2100	ECHAM5	A1B, A2, B1	0.088°	1
STAR	Statistic - empirical	2007-2060	ECHAM5	A1B	2342 climate and precipitation stations in Germany	100
Wettreg	Statistic - empirical	1961-2100	ECHAM5	A1B, A2, B1	274 climate stations and 1691 precipitation stations in Germany	20

In general, the dynamical models REMO and CCLM generate large deviations between the observed and simulated precipitation for the reference period [Gerstengarbe *et al.,* 2009]. In contrast, the simulated outputs from the model STAR have better agreement with the observed statistics, especially for temperature and air pressure [Gerstengarbe *et al.,* 2009]. Regarding the usefulness for hydrological impact simulations according to Bronstert *et al.* [2007], the STAR scenario is better suited for quantifying mean catchment runoff, and the dynamical models have advantage in modelling extreme conditions. Hence, in our study the simulation results using STAR scenario were used to analyse changes in the seasonal runoff and crop yield, whereas the outputs driven by other climate models (CCLM, REMO and Wettreg) were used to analyse the low flow conditions with related uncertainty. Notice that the model STAR generates 100 realizations for the A1B scenario, which help to quantify the uncertainty inherent in the climate scenario.

3.2 Soil and Water Integrated Model (SWIM)

SWIM (Soil and Water Integrated Model) is a process-based eco-hydrological model that combines the advantages of two previously developed models: SWAT [Soil and Water Assessment Tool, Arnold et al., 1993] for simulating the hydrological processes and vegetation growth and MATSALU [Krysanova et al., 1989] for the spatial disaggregation scheme and some of the nutrient sub-modules. SWIM simulates the major processes with a daily time step by disaggregating a basin to subbasins and hydrotopes, where the hydrotopes are sets of elementary units in a subbasin with homogeneous soil and land use types. A full description of the basic version can be found in Krysanova et al. [1998] and Krysanova and Wechsung [2000]. Here only the adjustment of net photosynthesis to higher CO_2 concentration and the adjustment of crop rotation under a warmer climate are described.

A temperature-dependent factor *α* was used to adjust the biomass-energy ratio for higher atmosphere CO_2 concentrations [Krysanova et al., 1999]. It was derived from a semi-mechanistic approach [Harley et al., 1992] for cotton and describes the interaction between CO_2 and temperature.

$$\alpha_{\cot} = \exp(a_2(CO_2^{i*} - CO_2^{i0}) - b_2\left[(CO_2^{i*})^2 - (CO_2^{i0})^2\right] + c_2(CO_2^{i*} - CO_2^{i0})T)$$
$$CO_2^i = 0.7 * CO_2^a$$

Where T is leaf temperature (°C), CO_2^i is the CO_2 concentration inside leaves (μmol mol^{-1}), CO_2^a is the CO_2 concentration in air, *0* and * indicate current and future concentrations and coefficients a_2, b_2 and c_2 equal 0.3898×10^{-2}, 0.3769×10^{-5} and 0.3697×10^{-4}, respectively. The cotton-specific factor α_{cot} was adjusted for winter wheat according to Kimball et al. [1995].

$$\alpha_{wheat} = \alpha_{\cot}^{0.6}$$

Regarding the crop rotation, crops are planted and harvested according to the current practice schedule [e.g. see statistical data from Voss, 2007] in the original SWIM version. However, under warmer conditions, the fixed schedule cannot be applied, because harvesting date would be shifted to earlier time. To overcome this shortcoming, the scheduling of winter wheat is governed by a harvest index depending on accumulated heat units. It means that the rotation scheme will be changed: winter wheat will be harvested earlier and the cover crop will grow earlier than in the current conditions.

The yield of winter wheat was calculated under different climate and CO_2 scenarios to investigate their impact separately and jointly. Besides the winter wheat – cover crop rotation, the winter wheat – summer barley rotation was also applied with fully flexible schedules based on their harvest indices. This allowed to account for the number of harvests (both winter wheat and summer barley) for each year. This attempt provides additional information on the possibilities of two yields per year in Germany in a warmer climate.

4 Results

4.1 Potential Water Availability under Climate Change

Fig. 2 compares the simulated average seasonal water discharge in the scenario period 2031-2060 and in the reference period 1961-1990 for six selected gauges. The light grey bounds include all simulated results from 100 realizations, and the dark grey bounds cover the 80 percentile of 100 runs. The black line is the median average daily discharge simulated with the 100 realizations. The red lines represent the average daily water discharge during the reference period. As shown in Fig. 2, river discharge is likely to increase in all rivers in the winter time, especially in the Ems and Weser. A robust trend seems to be that the recession of winter flow starts earlier in spring and lasts longer into late summer. In summer and autumn all the rivers tend to have 8 - 30% lower water discharge, especially from July to September. The main reason is higher evapotranspiration due to higher temperature and decrease of precipitation in summer. The earlier harvest of winter wheat and the following faster growth of cover crop aggravate the loss of soil water and decrease of runoff in these months. Among the six river basins, water discharge decreases in summer most dramatically in the Danube, Saale and Neckar basins (ca. 20 - 30% less water), where almost all 100 realizations show a lower level.

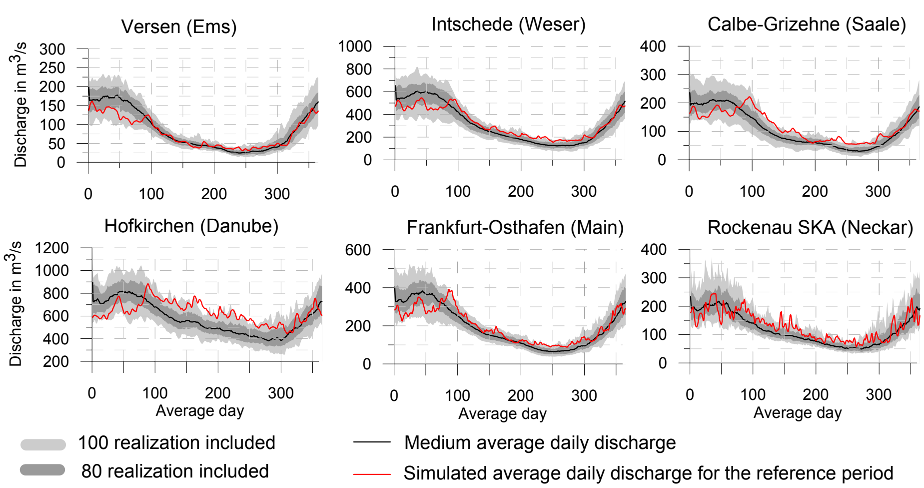

Figure 2 Seasonal water discharge in the scenario period (2031-2060) compared to the simulated discharge in the reference period (1961-1990) for six selected gauges (summer: days 152 – 243; autumn: days 244 – 334).

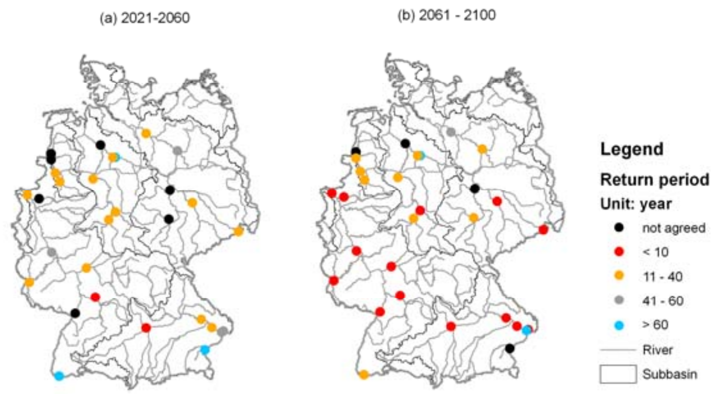

Figure 3 Return period of today's 50-year low flow in two scenario periods (median results agreed by ≥ 60% projections driven by CCLM, REMO and Wettreg scenarios).

Apart from the results driven by the STAR A1B scenario, the simulation results driven by other climate scenarios (generated by climate models REMO, CCLM and Wettreg under A1B, A2 and B1 emission scenarios) indicate more frequent extreme low flow conditions in the future [see also Huang et al., submitted]. Fig. 3 shows the median return period of today's 50-year low flow agreed by ≥ 60% of all projections. In the period 2021–2060 the current 50-year low flow is likely to occur more frequently (between 10 and 40 years) in most German rivers (Fig. 3a). In the second period 2061–2100, even more frequent low flows were projected in western, southern and central Germany with a return period less than 10 years (Fig. 3b). Based on all the simulation results above, we can conclude that low water availability in summer and autumn could become a much more severe problem in Germany under a warmer climate than now. Water stress is assumed to directly restrict crop growth and yield in the future.

4.2 Potential Winter Wheat Yield under Warmer Climate and higher CO_2 concentration

Yield of winter wheat was simulated in two basins: the Elbe and the Ems using the STAR A1B scenario under two assumptions: 1) impact of climate change only and 2) in combination with adjustment of net photosynthesis to higher CO_2 concentration. The CO_2 concentrations in the reference period (1961-1990, ca. 330ppm) and in the scenario period (2031-2060, ca. 500ppm) were estimated from the historical data and the A1B emission scenario, respectively. Fig. 4 shows the seasonal biomass production averaged for the scenario and reference period at one selected agricultural hydrotope in the basin Ems. If only climate change is considered, the biomass grows faster from March to June compared with the reference period due to higher temperature. The harvest time shifts from 5th August in the reference period to 4th June-28th July in the scenario period. However, the growth is hampered from July to August by the low water availability in summer, and the maximum biomass is about 20% lower than that in the reference period. When the CO_2 fertilization effect was considered in the simulation, the maximum biomass can reach almost the same level as in the reference period even though the further growth is still restricted by water availability. Hence, the effect due to increase in the CO_2 concentration can compensate for the negative impact of low water availability on the biomass production.

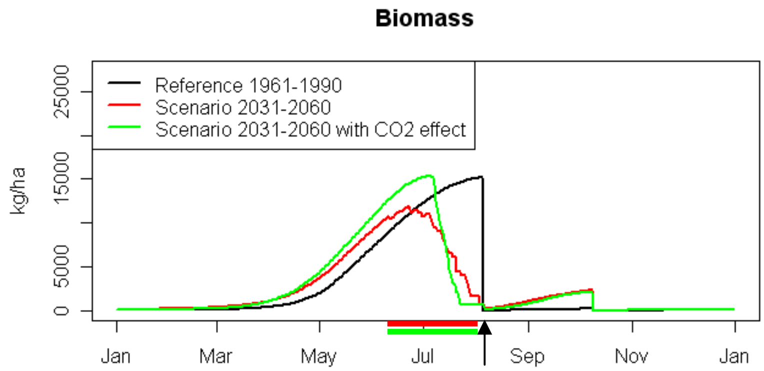

Figure 4 Seasonal biomass production averaged for the reference and scenario periods.

The impact of CO_2 fertilization is also pronounced when the winter wheat yield in the scenario period (averaged of all 100 realizations) is compared to the one in the reference period for the whole basin. Fig. 5 shows that in the basin Ems, the winter wheat yield would decrease by 6% of the yield on average in the current condition if only the climate scenario was considered. However, CO_2 fertilization enhances the yield with an increase of about 14% on average under the same climate scenario conditions. In a more continental basin, the Elbe, the water stress plays a bigger role than it in the maritime region (see Fig. 6) as water availability is even lower here (see Fig. 2). The total winter wheat yield decreases by 10% under the climate scenario only and increases by 9% in the combination of climate and CO_2 impact. In some sub-regions of the basin Elbe, the winter wheat yield in the scenario period is still lower than in the current conditions even with the CO_2 fertilization effect. Notice that the scenario period for winter wheat yield is from 2031 to 2060, when moderate changes in water availability were projected. More complicated change pattern may be expected for the last decades of this century due to even higher temperature, severer water stress and higher CO_2 concentration.

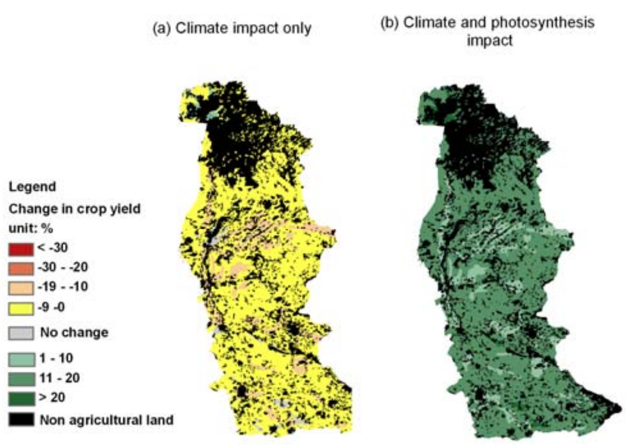

Figure 5 Difference maps for the winter wheat yield in the basin Ems between scenario period 2031-2060 (mean of 100 realizations) and the reference period 1961-1990 considering climate impact only (a) and climate and CO_2 impact (b).

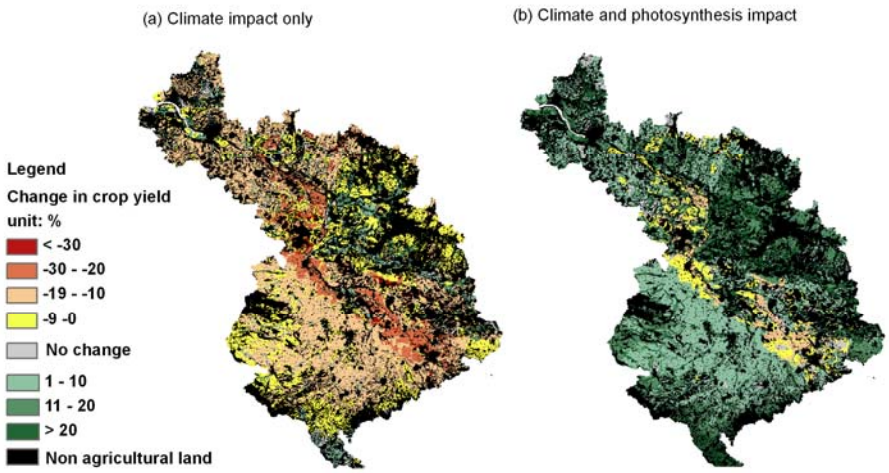

Figure 6 Difference maps for the winter wheat yield in the basin Elbe between scenario period 2031-2060 (mean of 100 realizations) and the reference period 1961-1990 considering climate impact only (a) and climate and CO_2 impact (b).

4.3 Potential of Two Yields per Year in the Basin Ems

The possibility of having two yields per year (winter wheat – summer barley) was tested for the basin Ems. Fig. 7 shows a share of arable land where two yields per year are possible. In the period 2008-2030 the two-yields-share is higher than 60% only for 8 years (35%), whereas the two-yields-share is higher than 80% of the whole arable land for 24 years of 30 (80%). This figure demonstrates the possible time frame and the extension of having two yields under a warmer climate in the north western Germany. However, the results should be treated with precaution, as this is only a projection under one climate change scenario. Other summer crops (e.g. maize), for which the optimal temperature for growth is higher than that of summer barley, will be tested in the next step.

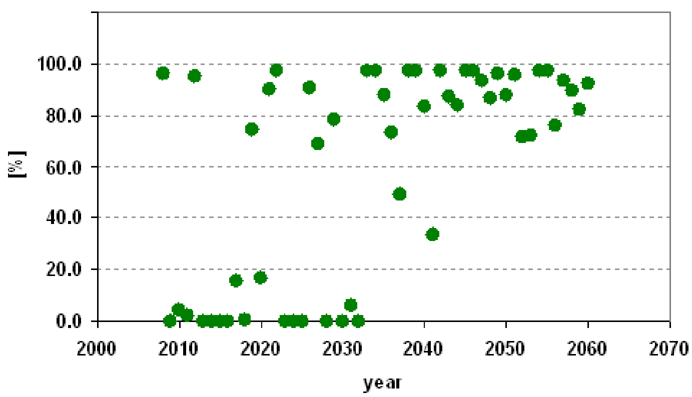

Figure 7 Share of arable land in the Ems basin having two yields per year (winter wheat – summer barley) projected by SWIM using STAR A1B scenario.

5 Conclusions

The study investigated the impact of a potential warmer climate on water availability and crop yield by using the eco-hydrological model SWIM and regional climate scenarios. As SWIM was developed specifically for climate change impact studies, it simulates the hydrological cycle and plant growth interactively, with adjustments for CO_2 fertilization effect and a changing crop management schedule.

Agreed by more than 60% of the projections driven by different climate downscaling models and emission scenarios, the water availability is likely to decrease in summer and autumn, especially in the Danube, Neckar and Saale river basins. The current 50-year low flow would occur more frequently (less than every 10 years) at the end of this century in the west, south and middle parts of Germany. Due to the higher temperature, crop growth is much faster in spring but hampered in summer by insufficient water supply. Hence, there is a potential to have lower winter wheat yield (ca. 6% lower in the basin Ems and 10% lower in the basin Elbe) in the future with drier and hotter summer periods. However, the negative impact of water stress can be compensated by CO_2 fertilization effect, and the winter wheat yield in the basin Ems and Elbe may increase by about 9-14% compared to the reference yield. In the warmer climate, there is a high potential to have two yields per year (winter wheat – summer barley) in the basin Ems after year 2030. Nevertheless, an adapted water management is required as it should ensure not only crop yield in a warmer climate but also sufficient water availability for other water users.

This paper shows a preliminary result on how crop yield can be varied with the influence of changed temperature, water availability and CO_2 concentration. There are some other impact factors which were not considered in this study, for example, water use efficiency of the vegetation due to higher CO_2 concentrations, introduction of irrigation measures, changes in crop types and varieties, and changes in agriculture management. Hence, a more comprehensive study on climate change impact on crop yield will be carried out for the whole Germany with careful validation of the crop yield for the current conditions. In addition, other methods estimating the CO_2 fertilization effect will be tested as this effect is still under discussion [Long et al., 2006]. Finally, the feedback of two-crop rotation on river discharge will also be evaluated.

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