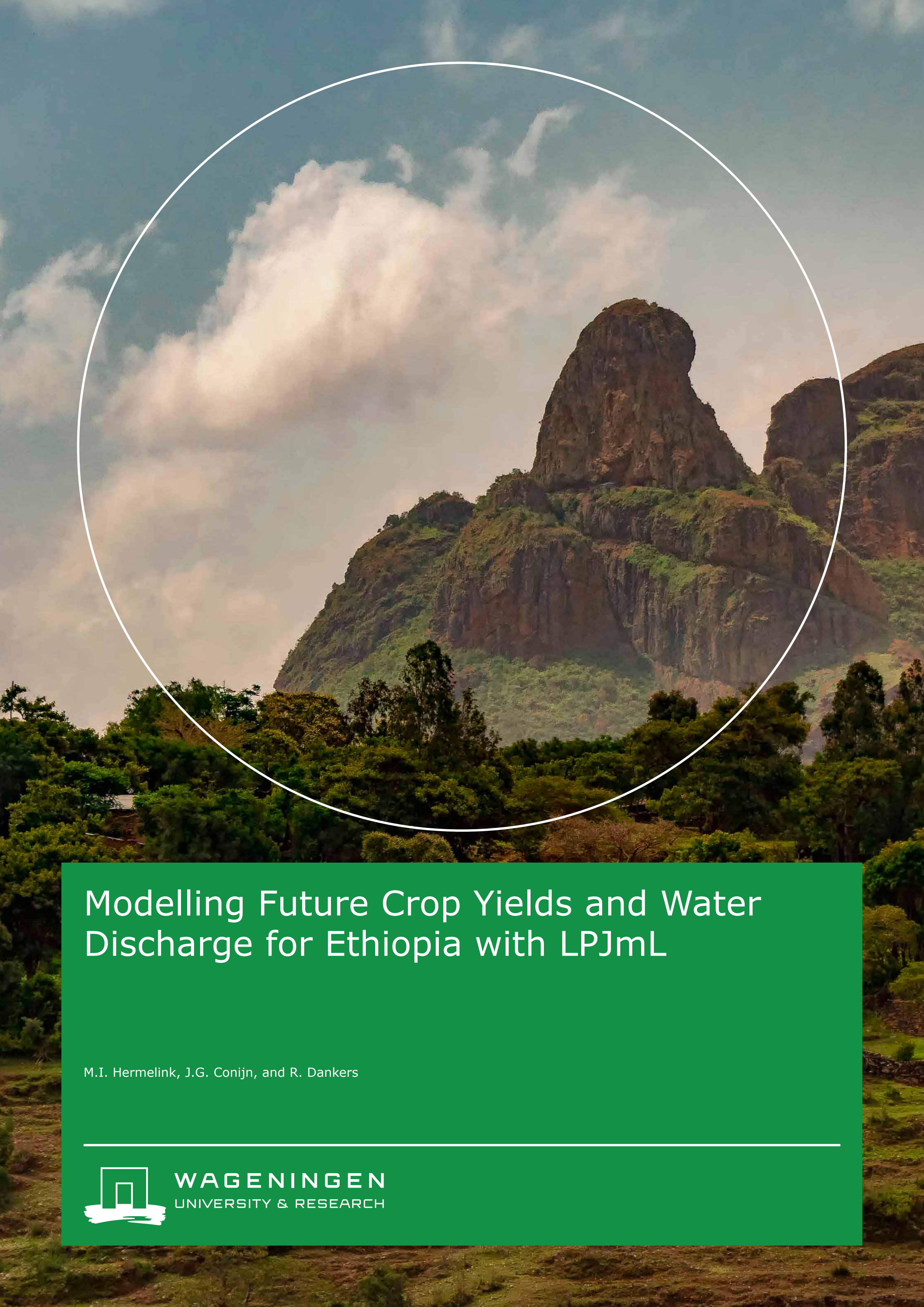

Modelling Future Crop Yields and Water Discharge for Ethiopia with LPJmL

M.I. Hermelink, J.G. Conijn, and R. Dankers

WAGENINGEN
UNIVERSITY & RESEARCH

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M.I. Hermelink[1], J.G. Conijn[1], and R. Dankers[2]

1 Wageningen Plant Research
2 Wageningen Environmental Research

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Ethiopia is facing looming climate changes in combination with steep population growth, with potentially a great impact on its food and water security. In this study we determine the expected effect of climate change on crop production, explore the potentials of crop production at different productivity levels, and link each production level to its potential impact on water demand and on the national water discharge. We find that the effect of climate change on actual yields is expected to be limited due to the projected annual rainfall increase. In addition, we find that crop productivity can be largely increased without the need for widespread irrigation, as crop management, rather than water availability, seems to be the main bottleneck towards higher crop yields. Due to the projected rainfall increase and the higher water use efficiency, increasing yields to rainfed potential levels could be achieved without decreasing the country's net water discharge.

Keywords: Ethiopia, LPJmL, food security, healthy diet, land use modelling, rainfed yield potential, national water discharge

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Contents

Summary

Ethiopia is facing looming climate changes in combination with steep population growth, with potentially a great impact on its food and water security. As the country is largely a water supplier to its neighbouring countries, water use within Ethiopia can impact water and food security in these countries and beyond. It is therefore of great importance to gain a better understanding on the possible developments in Ethiopia with regards to its food and water availability, and of the nexus existing between these two essential resources. In this study we determine the expected effect of climate change on crop production, explore the potentials of crop production at different productivity levels, and link each production level to its potential impact on water demand and on the national water discharge.

This explorative study was done using the Lund Potsdam Jena managed Land (LPJmL) land use model, and is the follow-up of a previous study for the project Multiple Scales and Extreme Events (Hermelink & Conijn, 2021). The current yields were calibrated based on FAOSTAT yields for Ethiopia. Four scenarios were simulated set in 2050: (a) business as usual, keeping actual yield levels, (b) rainfed potential yield, (c) irrigated potential yield with irrigation limited to actual surface water availability, and (d) unlimited irrigated potential yield. Each scenario was simulated given the driest and wettest climate projection for Ethiopia from the available projections of the Intersectoral Impact Model Intercomparison Project in the 3b protocol (ISIMIP3b, 2021). For each scenario, we evaluated the simulated crop’s yields, crop water and irrigation demand, and the impact on the national water discharge.

Based on the simulation results, the following main points could be concluded:
- Average annal crop productivity in Ethiopia’s main cropping season is not expected to be strongly affected by the changes in Ethiopia’s climate up to 2050. Both the driest and wettest climate change projections for the country predict an increase in annual rainfall as well as temperature, which for the simulated crops would not lead to yield declines.
- There is a large yield gap between the actual yields and the rainfed potential yields for most simulated crops. The yield gap between the irrigated and rainfed potential yield are relatively small, and the gap between limited and unlimited irrigation even smaller. This indicates that water availability is not the main bottleneck for crop production in Ethiopia, but rather crop management. A large increase in crop productivity could likely be achieved without the need for widespread irrigation.
- Increasing yields from the current to their rainfed potential level would not go at the expense of an increased crop water demand due to a higher water use efficiency at the rainfed potential production level. Crop yields could be increased further through widespread irrigation, but this would increase crop water use considerably.
- The increased precipitation in Ethiopia’s future projected climate would result in an increased net water discharge to its neighbouring countries compared to the current situation, regardless of the intensity level of crop production. Producing at the rainfed potential level would decrease the net water discharge only slightly compared to continued production at the current intensity level due to the higher water use efficiency at the rainfed potential, while widespread irrigation at this production level would decrease the country’s net water discharge by almost 30%.

To further sharpen the conclusions of this study, it would be necessary to look further into the physiological calibration of especially the root crops and of grass, to simulate multiple growing seasons, and to improve simulated basin discharge. A more accurate simulation of crop productivity would in turn allow the comparison of future food production estimates to future food demand, in order to identify food security issues. To make predictions on the options to meet healthy diets it would also be necessary to include fruit and vegetable crops, which LPJmL does not simulate.

1 Introduction

Ethiopia, as the rest of the world, is facing looming climate changes, with potentially a great impact on its food and water security. Besides this, Ethiopia, as the rest of Africa, is also facing a large increase of its population in coming decades, up to twice or more its current level. As Ethiopia is largely a water supplier to its neighbouring countries, water use within Ethiopia can impact water and food security in these countries and beyond. It is therefore of great importance to gain a better understanding on the possible developments in Ethiopia with regards to its food and water availability and use, and of the nexus existing between these two essential resources. In this technical report, we describe the steps and results in modelling crop production and water discharge in Ethiopia using the Lund Potsdam Jena managed Land (LPJmL) land use model. This is the follow-up of the study '*Modelling crop yields and water balances for Ethiopia with LPJmL*' for the project Multiple Scales and Extreme Events (Hermelink & Conijn, 2021). LPJmL was used to perform an explorative study of alternative crop production scenarios for different climate change projections for Ethiopia and their corresponding impacts on food security and the national water discharge. The following research questions were investigated:

1. What is the current crop production in Ethiopia, and how would it be affected by climate change up to 2050?
2. What would be the rainfed potential crop production in Ethiopia in 2050, given its climate change projections?
3. What would be Ethiopia's irrigated potential crop production in 2050, given its climate change projections, and to what extent is this limited by the available water?
4. How would Ethiopia's water discharge be affected by crop production at the rainfed and irrigated potential production level compared to the current production level?

In the next chapters we describe the Lund Potsdam Jena managed Land (LPJmL) land use model, the scenarios that were simulated to answer the research questions, the input data preparation and the calibration process (Section 2.1). We report on simulation results (Section 3), and finally make conclusions and recommendations for further research (Section 4).

2 Material and Methods

2.1 The LPJmL Model

The Lund Potsdam Jena managed Land model is a dynamic vegetation model developed by the Potsdam Institute for Climate Research (PIK), usually applied at the global or regional scale. In this case, we have used it for an area covered by Ethiopia and its outflowing basins, including the Nile. Inputs for the model consist of gridded data on climate, terrain (elevation, basin network, soil type), and land use. LPJmL uses these data to simulate growth and productivity of natural and agricultural vegetation at grid cell level through water, carbon, and energy fluxes. The resolution used to model at a regional level like Ethiopia is 5 arcmin (10x10 km at the equator). The agricultural vegetation is simulated as crop functional types (CFTs), which are clusters of crops that have been grouped based on their growth characteristics. Natural vegetations is simulated as plant functional types (PFTs), also representative for clusters of plant types. Cells can be covered by both CFT and PFT fractions. LPJmL can be used to simulate a wide range of biophysical processes, but for this study we have used it to simulate crop yields at the irrigated potential, rainfed potential (water limited), and actual level, and their corresponding national water discharge. Crop production is simulated for each cell's main growing season, with secondary growing seasons simulated as grass. For a detailed explanation of LPJmL, Schaphoff et al. (2018) can be consulted. This study made use of LPJmL 4.0.002, which was available as open access on PIK's LPJmL github repository. *[Above section is largely taken from Hermelink and Conijn (2021).]*

2.2 Scenarios

To answer the research questions, we have modelled five scenarios with LPJmL, each simulated for two different climate projections:

a. The **current situation scenario**, set in the current time, with climate, production intensity level, and land use modelled as they are now. For this scenario, we used the W5E5 historical climate dataset (Lange, 2019), running for the period of 1979 to 2016. We assume land use as reported for cropland by MapSpam in 2017 (IFPRI, 2020) and grassland by EarthStat in 2000 (Ramankutty et al., 2008). We set the crop production intensity level such that nationally aggregated yields equal FAOSTAT-reported yields for the same period, averaging over the years 2000 to 2016.
b. A **business as usual scenario**, set in 2050, to explore the effect of climate change on food production and the water discharge if the current production system in maintained. We keep land use and the production intensity level as in the current situation (see A), and model crop production for the driest and wettest climate change projections of the Intersectoral Impact Model Intercomparison Project (ISIMIP3b, 2021).
c. A **rainfed potential scenario**, set in 2050, to explore Ethiopia's crop production potential given an overall intensification of its crop production systems, but without increasing irrigated crop area. Although in this scenario we maintain the currently irrigated crop areas, this is such a small fraction of the total crop area (
d. **Table 3**) that we still call this Ethiopia's rainfed potential. For this scenario, we assume land use as it is now (see A), and follow the same two climate change projections as in B, but we assume the maximum production intensity level (LAImax) possible for all crops.
e. An **irrigated potential scenario**, set in 2050, to explore Ethiopia's crop production potential given an overall intensification of its crop production system, including a widespread implementation of irrigation. We keep crop area distribution as it is now, but assume all crop areas are irrigated. We set the production intensity level (LAImax) at its maximum level and follow the same climate change projections as in the previous scenarios.
f. A **unlimited irrigation potential scenario**, set in 2050, to explore the absolute potential crop production in Ethiopia if water availability for irrigation is unlimited. The difference between this potential

level and the limited irrigation potential (D) shows to what extent water availability is a bottleneck for crop production at the potential level. For this scenario, we assume crop area distribution as it is now but with all crop areas irrigated. We use the setting of unlimited irrigation in LPJmL. Note that due to this hypothetical assumption of unlimited water, national and basin water discharge of this scenario are not realistic nor relevant.

2.3 Input Data

2.3.1 Land Use

LPJmL requires a land use map indicating each the fraction of each cell covered by each CFT. We refer to the sum of the areas of all CFTs, including grassland, as the cell's crop or cropping area.

MapSPAM
The CFT cell fractions for all edible CFTs (1 to 13) were determined based on the Spatial Production Allocation Model (MapSPAM) dataset for Sub-Saharan Africa in 2017 (IFPRI, 2020). The database contains gridded data at a 5 arcmin resolution of the physical and harvested areas of 42 crops. The physical area refers to the actual area where a crop is grown, without taking into account how often the crop was harvested from that area. The sum of all physical areas of the crops in a grid cell is therefore equal or smaller than the cell size. The harvested area is at least as large as the physical area, but can be larger if the crop is harvested more than once in a single year. The sum of the harvested areas of all crops in a grid cell can therefore be larger than the total cell size. As the open source version of LPJmL can only simulate a single growing season for each CFT, it was necessary to use the physical areas rather than the harvested areas of the crops. This has the disadvantage that some of the crop production is not simulated (second growing seasons). The crops in the MapSPAM database were grouped into CFTs according to Table A1 in the Annex. The physical areas of each CFT were transformed to rainfed and irrigated cell fractions.

EarthStat
As the MapSPAM database did not contain grassland area, the cell fractions for the CFT Managed Grass (CFT 14) were estimated based on EarthStat agricultural grassland area data in the year 2000 (Ramankutty et al., 2008). A cell fraction of the grass CFT was assumed to follow EarthStat data, unless the sum of the MapSPAM and EarthStat cell fractions was larger than one. In that case, the grass CFT cell fraction was assumed to be the difference between 1 and the total MapSPAM cell fraction. It was assumed that none of the grassland is irrigated. Note that the open source version of LPJmL assumes grassland CFT cell fractions are Managed Grass, which is periodically mowed (see LPJmL Wiki - Grazing), while EarthStat grassland data does not differentiate between managed and extensively grazed grassland.

Irrigated Scenarios
For the irrigated scenarios (Scenarios D and E), we maintain the same distribution of CFT areas, but assume all areas are irrigated.

2.3.2 Climate and CO_2

Current climate
For Scenario A, the current situation in Ethiopia, the W5E5 historical climate dataset was used (Lange, 2019), as this is the dataset with which the future climate scenario's were bias-corrected. Variables retrieved from the dataset were temperature, precipitation, and short and long wave downwelling radiation, all in daily time steps. Atmospheric CO_2 concentrations for the current climate were obtained from Wageningen Environmental Research.

Future Climate
For Scenarios B to E, we used two climate change projections selected from the projections provided by the Intersectoral Impact Model Intercomparison Project in the 3b protocol (ISIMIP3b, 2021). Projections were available from five Global Circulation Models (GCMs) for three combinations of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) (see Figure A1 in Annex for all existing

combinations). The two projections were selected by comparing the average annual precipitation in a rectangle encompassing Ethiopia (Figure A2 in Annex) across all the available projections (Table 1). The projections with the lowest and highest annual precipitation were selected to represent the driest and wettest climate change projections respectively for Ethiopia, i.e. GFDL_ESM4 – SSP585 (driest) and UKESM1_0_LL – SSP585 (wettest). Variables retrieved from the projections were temperature, precipitation, short and long wave downwelling radiation, and atmospheric CO_2 concentration.

Table 1 *National annual precipitation (mm/y) for Ethiopia, averaged between 2036 to 2065 as projected for the Shared Socioeconomic Pathways (SSPs) 126, 370, and 585 by five Global Circulation Models (GCMs). The driest and wettest projections are highlighted in blue.*

GCM	SSP126	SSP370	SSP585
GFDL_ESM4	674	677	644
IPSL_CM6A_LR	743	725	779
MPI_ESM1_2_HR	683	679	708
MRI_ESM2_0	711	689	737
UKESM1_0_LL	843	857	909

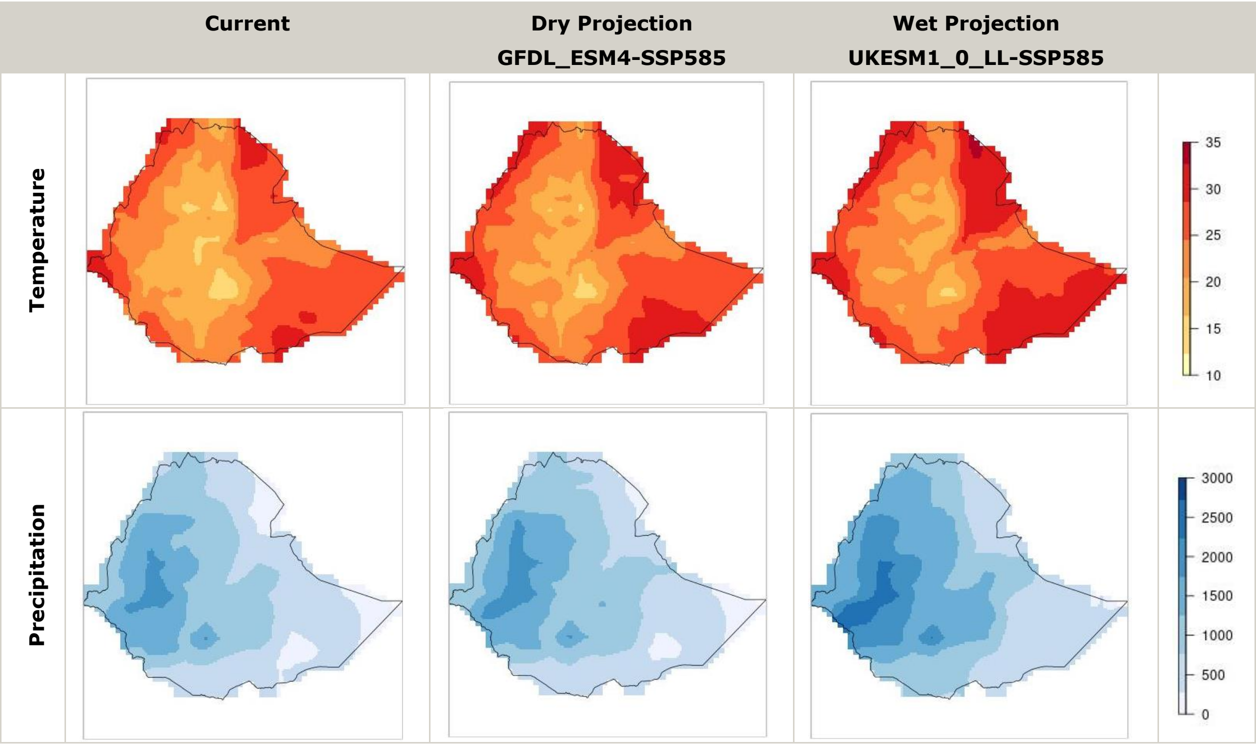

Figure 1 *Spatial distribution of average annual temperature (top, °C) and precipitation (bottom, mm/year) in Ethiopia in the current situation (2000-2016, Scenario A) and in the dry and wet projections for the future scenarios (2036-2065, Scenarios B to E).*

2.3.3 Other data

For all other input data used in the LPJmL scenarios, the previous technical report can be consulted (Hermelink & Conijn, 2021).

2.4 Spin-ups and Historical Run

Before performing the simulations for the outlined scenarios, we ran two spin-up simulations and a historical simulation from 1900 to 1979 to reach water and Carbon pool balance equilibria and to obtain realistic soil properties as a result of agricultural activities. More details on these simulations can be found in the previous technical report (Hermelink & Conijn, 2021).

2.5 Calibration

LPJmL was calibrated through two different parameters, using historical FAOSTAT yields as a reference.

2.5.1 Base Temperatures

The base temperature (BT) is a parameter provided by LPJmL for each CFT. We made adjustments to the BT of the CFTs Tropical Cereals, Maize, Temperate Roots, and Tropical Roots. The BT of the CFT Tropical Cereals was changed from the original 10 °C to 7.8 °C, which is the base temperature of teff, i.e. the main tropical cereal grown in Ethiopia (Paff & Asseng, 2019). The base temperature of maize was variable between 5 °C and 15 °C, which we set to 10 °C following Ogutu et al. (2018). The BT of Temperate Roots was changed from 3 °C to 5.5 °C to account for Ethiopian potato varieties (Getahun et al., 2020). The CFT Tropical Roots were originally parameterized for cassava, which is not grown in Ethiopia. The CFT parameterization was therefore adapted to parameterize sweet potato, a more commonly grown crop, and its BT was changed from 15 °C to 12 °C (Raymundo et al., 2014). Its lower and upper limit temperatures for optimum photosynthesis were also changed from the original 20-45 °C range to 8-33 °C, keeping the same range width but averaging the optimum 21.5 °C as indicated by Alvim and Kozlowski (2013).

2.5.2 Maximum Leaf Area Index

The main parameter through which the yield of LPJmL is calibrated is the Maximum Leaf Area Index (LAImax) (Fader et al., 2010). The Leaf Area Index (LAI) is the leaf area per unit ground area, and is a measure of how efficiently plants can capture incoming light. In LPJmL, the LAImax parameter of a CFT is its maximum attainable LAI, and is defined as a value ranging from 1 to 7. As LPJmL does not model any crop management practices other than irrigation (such as fertilization, weeding, or pest and disease control), LAImax is used as a proxy to indicate production intensity level. The parameter must be indicated specifically for each CFT in each country and there is only one value for the whole country. LAImax is directly coupled to two other parameters: the Maximum Harvest Index (HImax) and the AlphaA (α-a). The maximum harvest index indicates the fraction of the aboveground biomass belonging to the harvestable product in the absence of water stress, and is used as a proxy for crop variety. AlphaA is a parameter that scales biomass production from leaf level to stand level, following LAImax. Both the HImax and AlphaA are also CFT and country specific. Together, the LAImax, HImax, and AlphaA parameters are a package emulating the effect of management on crop production. As HImax and AlphaA are directly dependent on LAImax, only the LAImax requires calibration. For more detailed information on LAImax, HImax, AlphaA, or the calibration process, Fader et al. (2010) can be consulted. *[Above section was taken from Hermelink and Conijn (2021)]:*

LAImax values for each CFT, except Managed Grass and Others, were calibrated for Ethiopia by running LPJmL at all seven integer LAImax levels. The simulated yields of each CFT at each LAImax were averaged for the years 2000 to 2016 at the national level of Ethiopia. The year 2000 was selected as the cut-off year as a compromise between having enough years (= 17) to average out climatic variations, and reflecting recent increases in productivity in Ethiopian crop production compared the decades between 1980 and 2000 (Taffesse et al., 2012). The average yield of each CFT at each LAImax was compared to the average yield of each CFT according to FAOSTAT data for the same period. To compute the average FAOSTAT yields, all crops produced in Ethiopia were grouped into the CFTs as shown in Table A2 in the Appendix. The average yield was then computed by calculating total production across all crops in the CFT and dividing by the total harvested area across all crops for each year, and then averaging over the years. We compared the simulated yields at all LAImax levels to the FAOSTAT average yield and selected the two LAImax values the lead to yields closest to the FAOSTAT yield, i.e. the LAImax range. We then assumed a linear relation between the CFT yield and LAImax within the selected LAImax range, and computed the LAImax value corresponding to the exact FAOSTAT yield. These LAImax values were used for scenarios A and B, which simulate crop yields at the actual level. Note that the LAImax for sugarcane was set at 7, which is not in line with the relatively low LAImax values of the other CFTs. This is due to the large difference between the simulated sugarcane yields at all LAImax values and the FAOSTAT yield, possibly as a result of differences in crop parameterisation between LPJmL and FAOSTAT (e.g. harvest index, dry matter content, or physiological parameterisation) (Lapola et al., 2009). However, as sugarcane covers a very small area in Ethiopia (**Table 3**) the crop parameterization was not looked into further.

The CFT Managed Grass cannot be calibrated with LAImax, as it is not dependent on LAImax in LPJmL. Furthermore, we lack data on national grass yields, such as the crop yields from FAO. As an alternative, the modelled historical yield values were checked to be in line with the order of magnitudes for grassland production in Ethiopia as reported by Agza et al. (2013). Average annual grassland yield between 2000 and 2016 simulated by LPJmL was 12.8 ton fresh matter per hectare, while Agza et al. (2013) found grass yields in Ethiopia’s Northwest lowlands to be between 12.6 and 24 ton fresh matter per hectare. The simulated yield is therefore within the correct range, although on the low side, but given the fact that the simulated grass yield also includes Ethiopia’s more arid regions in the eastern part of the country, this could be expected. The CFT Others is simulated as grass as well, and can therefore not be calibrated either.

Table 2 *Simulated average yield (ton/ha) for 12 crop functional types (CFT) with LPJmL at Maximum Leaf Area Index (LAImax) 1 to 7, average yields according to FAOSTAT (ton/ha), and calibrated LAImax value for scenarios A and B. Averages were computed over years 2000 to 2016. The two simulated yields closest to the FAOSTAT yield for each CFT are highlighted and were used to computed the calibrated LAImax. Yields of the CFT Sunflower are not available (na) because the production area in Ethiopia was zero (IFPRI, 2020).*

	LAImax								**FAOSTAT**	**Calibrated**
CFT	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Yield**	**LAImax**
Temperate Cereals	0	1.5	3.3	5.1	6.9	8.6	10.4	12.1	1.85	1.18
Rice	0	1.4	2.9	4.3	5.7	7.0	8.4	9.7	3.94	2.73
Maize	0	0.7	2.5	4.5	7.0	9.2	10.1	10.9	2.54	2.04
Tropical Cereals	0	0.7	1.2	1.8	2.4	3.0	3.6	4.2	1.54	2.55
Pulses	0	1.0	2.1	3.2	4.4	5.5	6.7	7.9	1.16	1.16
Temperate Roots	0	14.4	25.9	35.5	44.7	53.7	62.5	71.0	10.51	0.73
Tropical Roots	0	6.6	12.6	17.9	23.0	28.0	33.1	38.0	19.17	3.25
Sunflower	na	na	na	na	na	na	Na	na	1.06	na
Soybean	0	0.6	1.1	1.7	2.4	3.1	3.8	4.6	1.48	2.57
Groundnuts	0	1.0	1.9	2.7	3.4	4.1	4.9	5.6	1.37	1.40
Rapeseed	0	0.8	1.8	2.7	3.6	4.5	5.5	6.4	1.36	1.58
Sugarcane	0	3.6	6.6	9.7	12.8	16.0	19.3	22.6	63.37	7.00

2.6 Production Intensity Levels

For scenarios simulating the current production intensity level in Ethiopia (Scenarios A and B), we used the calibrated LAImax values. For scenarios simulated at the rainfed and irrigated potential level (Scenarios C to E), we used an LAImax value of 7 for all CFTs. As setting the LAImax value of Managed Grass (CFT 14) and Other Crops (CFT 13, simulated as Managed Grass) was not possible, its potential was estimated by changing its AlphaA value. For CFTs 1 to 12 the LAImax and AlphaA parameters are linked through Equation [1], with an AlphaA of 0.4 at an LAImax of 1 and an AlphaA of 1 at an LAImax of 7. For Managed Grass (CFT 14) and Other Crops (CFT 13), the AlphaA value was therefore manually increased from its original value of 0.4 to 1 in order to simulate potential production.

$$AlphaA = 1 - (0.1 * (7 - LAImax)) \qquad [1]$$

2.7 Output Processing

2.7.1 General

Outputs were averaged from 2000 to 2016 for the current climate and from 2036 to 2065 for the future climate scenarios. All averages were estimated calculating first averages in each year and then averaging over all the years in the time period.

2.7.2 Yield

LPJmL generates yield output in grams of harvested carbon per square metre per year (g C/m2/y). These results were transformed to tons of fresh weight per hectare according to Equation [2], with Y_C and Y_{FW} the yield in the carbon and fresh weight units respectively, *C* the carbon content (g C/g dry matter), and *DMC* the dry matter content (g dry matter/g fresh weight). The carbon content was assumed to be a constant value of 0.45 for all CFTs, following Fader et al. (2010). The dry matter content for each CFT can be found in Table A3 in the Annex and was assumed to be independent of the simulated climate situation. *[Above section was taken from Hermelink and Conijn (2021)]*

$$Y_{FW} = Y_C * \frac{1}{C} * \frac{1}{DMC} * 10^{-2} \qquad [2]$$

2.7.3 Precipitation Surplus

The average national yearly evapotranspiration in Ethiopia's crop area (*ETavg*, mm/year) was computed through Equation [3], with ET_{CFTi} the annual evapotranspiration (mm/yr) of a CFT in cell *i*, $fCellArea_{CFTi}$ the fraction of cell *i*'s area covered by a specific CFT, $fCropArea_{CFTi}$ the fraction of cell *i*'s crop area covered by that CFT, and $Area_i$ the total area of cell *i* (km^2). Average national yearly precipitation on the crop area ($Prec_{avg}$, mm/year) was computed following Equation [4]. The difference between the annual precipitation and evapotranspiration was defined as the precipitation surplus for the area in Ethiopia covered by crops and grasslands.

$$ET_{avg} = \sum_i \left(\sum_{CFT} (ET_{CFTi} * fCropArea_{CFTi}) * \frac{fCropArea_i * Area_i}{\sum_i (fCropArea_i * Area_i)} \right) \qquad [3]$$

$$Prec_{avg} = \sum_i \left(Prec_i * \frac{fCropArea_i * Area_i}{\sum_i (fCropArea_i * Area_i)} \right) \qquad [4]$$

with:
$fCropArea_{CFTi} = \frac{fCellArea_{CFTi}}{\sum_{CFT} fCellArea_{CFTi}}$ *and* $fCropArea_i = \sum_{CFT} fCropArea_{CFTi}$

2.7.4 National Water Discharge

2.7.4.1 Basin Discharge Validation

To determine the national water discharge, we first evaluated the quality of the basin discharge results as simulated by LPJmL. A basin's discharge is the result of water infiltration into the soil in the whole area draining into that specific basin, including both areas for agricultural vegetation (CFTs) and natural vegetation (PFTs). We compared average monthly simulated and measured discharge values at basin measuring stations from the Global Runoff Data Centre (GRDC, 2022). We selected all stations with more than two measuring years. The selected stations are Sudan Border, Lake Tana, Gambella, Gode, Hombole, Metahara, Melka Sedi, and Adaitu (measuring years for each station in Table A4 in Appendix). The coordinates of the stations were examined visually in QGIS, and where necessary corrected slightly to fall on the corresponding grid cell of the river network used as input for LPJmL (Figure A3 in Appendix). The monthly discharge output of LPJmL at the station coordinates was averaged across the measured years of each station and transformed to m^3/s, to compare to the measured discharge values in the same years.

The basin discharge of the LPJmL simulations does not take into account consumptive water use for industrial and domestic purposes. We estimated the order of magnitude of the consumptive water use using values at national level from AQUASTAT (2022). Annual industrial and domestic water use values from 2010 to 2019 were averaged and transformed from m3/year to m3/s. We compared the estimated consumption values with basin discharge to determine to what extent the consumptive use can explain differences between simulated and measured basin discharge values.

2.7.4.2 National Water Discharge

The national water discharge was determined as the net water discharge to bordering countries. It was estimated by visually assessing the HydroSheds river network (Lehner et al., 2008) in QGIS and locating all basin border crossings (Figure A3). For each scenario, the discharge flows in and out of Ethiopia at those points was added, resulting in the net discharge at national level.

2.7.5 Total Irrigation

The total irrigation across Ethiopia was estimated for each scenario by multiplying the irrigation level (mm/year) at each grid cell with its corresponding irrigated area and calculating the sum (m3/year) of all grid cells in Ethiopia.

3 Results and Discussion

3.1 Crop Areas

Total physical areas of each CFT as used for LPJmL simulations are reported in **Table 3**, along with the percentage irrigated area. We also report each CFT's harvested area along with the average harvested area reported in FAOSTAT as a reference. Based on area, Ethiopia's main crop CFTs are tropical and temperate cereals (teff and wheat respectively), maize, and pulses. The CFT Tropical Roots stands out due to the relatively large difference between the MapSPAM and FAOSTAT harvested area, suggesting a possible error in the simulated area. Some smaller crops are groundnuts, temperate roots (potato), soybean, and sugarcane. Sunflower and crops for bio-energy production were not reported to be produced. All other crops produced in Ethiopia were grouped under the CFT 'Other Crops', which represents a significant cropping area, but cannot be accurately modelled with LPJmL. The CFT managed grass covers by far the greatest area, as Ethiopia has some large expanses of areas that are too arid for crop production but that can sustain grass. However, these areas are grazed extensively, so it is debatable whether the total area of grass should be classified as managed grass.

Table 3 *Physical and harvested areas (ha) in Ethiopia of LPJmL's Crop Functional Types (CFTs) and the percentage of the physical area irrigated (IFPRI, 2020; Ramankutty et al., 2008). The last column contains the average harvested areas between 2000 and 2016 according to FAOSTAT (2022). Na = not available.*

CFT Code	CFT Name	Physical Area (ha)	Physical Area Irrigated (%)	Harvested Area (ha)	Harvested Area FAOSTAT (ha)
1	Temperate Cereals	2,259,249	0.57	2,678,975	2,566,785
2	Rice	35,857	0.65	47,570	29,197
3	Maize	1,219,019	1.95	2,169,875	2,291,083
4	Tropical Cereals	4,338,335	0.69	5,457,558	4,786,879
5	Pulses	1,065,936	0.27	1,582,607	1,010,942
6	Temperate Roots	66,535	7.72	66,545	62,249
7	Tropical Roots	782,977	1.00	1,072,288	118,641
8	Sunflower	0	0.00	0	6,818
9	Soybean	38,433	0.41	38,436	23,437
10	Groundnuts	79,010	3.42	79,019	53,597
11	Rapeseed	32,333	0.08	32,333	26,722
12	Sugarcane	20,570	26.64	20,573	25,058
13	Others	2,315,460	3.92	2,592,581	2,896,247
14	Managed Grass	19,668,042	0.00	19,668,042	20,000,000
15	Bio-energy Grass	0	0.00	0	na
16	Bio-energy Trees	0	0.00	0	na

Note: areas of CFT up to 13 refer to 2017 (IFPRI, 2020), that of Managed Grass (CFT 14) to for 2000 (Ramankutty et al., 2008).

3.2 Yields

The yields of the simulated CFTs are reported in Figure 2 in the current situation and in 2050 at the actual, rainfed potential, and limited as well as unlimited irrigated potential. The difference in yields between '2008 - Current' (scenario A) and '2050 - BaU' (scenario B) is due to the projected climate changes (with a wet and dry variant), the difference between '2050 - BaU' (scenario B) and '2050 - Pot Rainfed' (scenario C) is due to intensification (without additional irrigated areas), the difference between '2050 - Pot Rainfed' (scenario C) and '2050 - Pot Irrig (Lim)' (scenario D) is due to additional irrigation with available water and the difference between '2050 - Pot Irrig (Lim)' (scenario D) and '2050 - Pot Irrig (Unlim)' (scenario E) is caused by assuming no limitation to available water for irrigation. This latter scenario shows the maximum effect of limited water availability for irrigation.

As a reference we have added Table 44, which reports the irrigated potential yields in Ethiopia of the CFTs as reported by the global yield gap atlas (GYGA), with unlimited irrigation. For CFTs where potential yields were not available, we have added the national average yields of the top yielding countries for each crop as an alternative reference.

Some points to note on the quality of the estimates:

- Yields at the actual level (Business as Usual scenario) are close to current levels, with only small increases or decreases as a result of a changing climate. A notable exception of this is sugarcane, which does increase considerably in the BaU scenario. This could be explained by the fact that its LAImax value was set at 7 (see Section 2.5.2), and that the increase in rainfall in the climate projections allowed a substantial increase in crop yield.
- Yields at the potential level, both rainfed and irrigated, in general seem to over-estimate yields when compared to the reference values in Table 44. The over-estimation is smallest for the cereals, pulses and oilcrops, with simulated potential values still generally in a feasible range, and largest for the root crops and grass, where the simulated potentials greatly exceed realistic production levels. Some possible explanations for this over-estimation are:
  - The LAImax values at the potential (rainfed and irrigated) yield levels were set at seven for all crops, which is likely unrealistically high for some of them.
  - For grass, it is likely that the potential yield overestimation is caused by the increase of the parameter AlphaA to 1, which seems unrealistically high for Ethiopia. This is not a standard procedure for LPJmL simulations, as grass is generally not simulated at different potential levels with this model. Moreover, grass is simulated as 'managed grass', with periodic mowing, while in reality the grassland areas are grazed very extensively.

Despite the quality considerations on some of the CFT yields, the following conclusions can be made from the results:

- At the actual yield level (BaU scenario), there is little to no impact of the change in climate on the average yields. The predicted decreases in yields are small, and in the case of some crops they are positive. This might be explained by the fact that the average rainfall levels in Ethiopia are projected to increase (see Figure 1 and Table 15), even in the driest projection. Nonetheless, it should be noted that the reported values are averaged over a period of 30 years and across the whole country's crop area, which can average out the effect of localized or temporary droughts. It should be further explored what the effect is of the climate projections on actual yield levels in smaller areas and in individual years.
- Even taking into account LPJmL's over-estimation of the potential yields, the results indicate that a large increase in productivity can be achieved without an increase in irrigated area. Even if the rainfed potentials are halved, for example, for most CFTs that would still leave room for significant productivity growth compared to the actual yield levels (BaU).
- At the potential level, the increase in yields as a result of irrigation is limited for most crops. This can be explained by the fact that most crop production in Ethiopia takes place in areas where average annual rainfall is sufficient to sustain crop production. The CFT benefitting the most from added irrigation would be grass, which grows in the most arid regions of the country.
- The relative effect of unlimited irrigation compared to limited irrigation is also small. This indicates that the availability of surface water for irrigation would not be very limiting for crop production at the potential level.
- Overall, the results indicate that water availability is not the main bottleneck for crop production in the main growing season of Ethiopia, but rather crop management. This is in line with the average annual rainfall values between 600 and 900 mm, which should be sufficient for crop production.

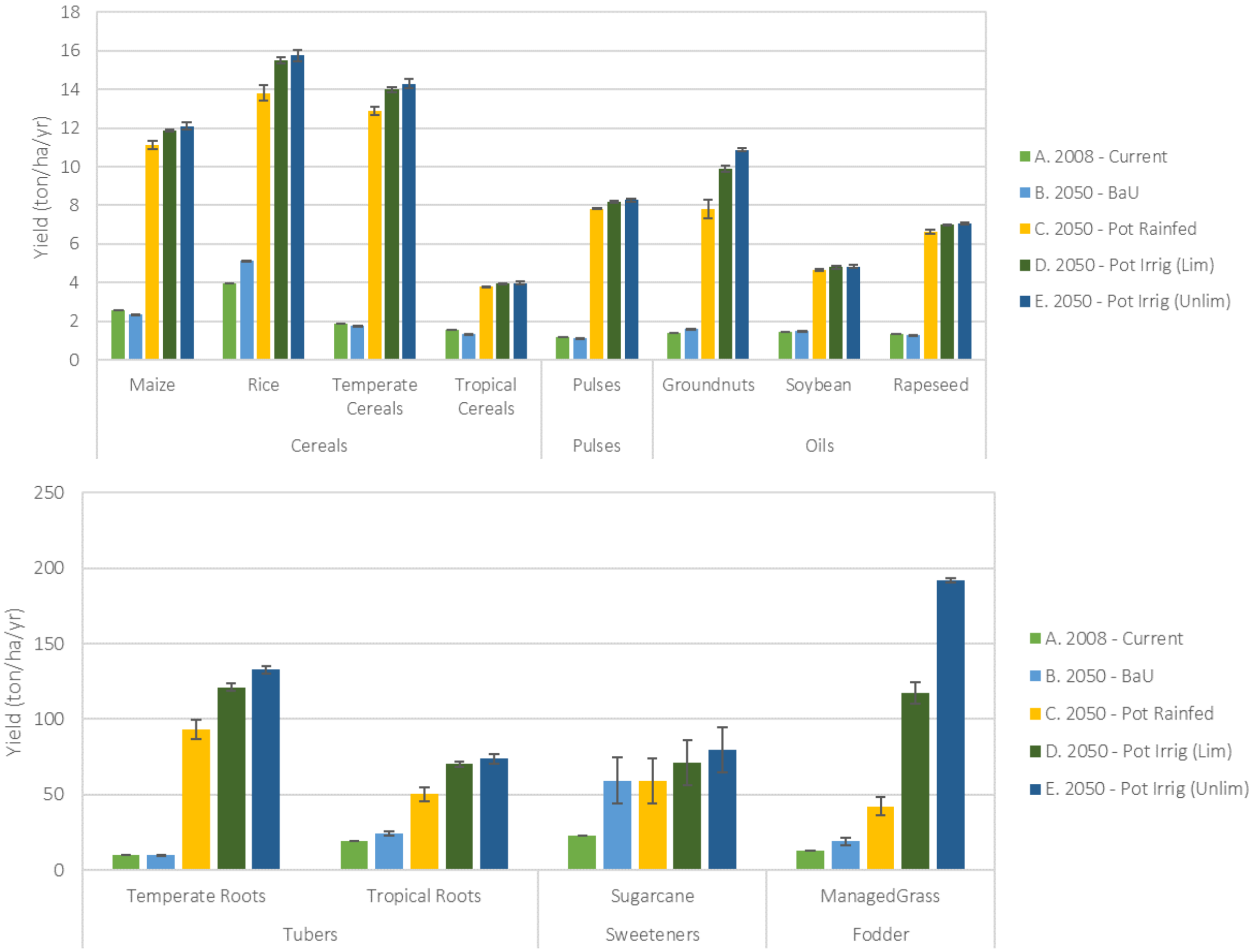

Figure 2 *Annual yield simulated by LPJmL of the Crop Functional Types (CFTs) grown in Ethiopia in scenarios A to E, with cereals, pulses, and oil crops in the top panel and tubers, sweeteners, and fodders in the bottom panel. Yield values are reported in fresh weight (dry matter content in Table A3 in Appendix). Values for the current scenario are averaged across 2000 – 2016 and for the future scenarios from 2036 to 2065. Bars represent values averaged across both simulated climate projections, while error bars represent the difference between the two projections.*

Table 4 *Potential yield with unlimited irrigation as predicted by LPJmL and reference yields as comparison, both in ton fresh weight/ha per growing cycle (CFT 1- 11) or per year (CFT 12 & 14). Cereals and pulses are compared to potential yields for Ethiopia of the Global Yield Gap Atlas (GYGA) and other CFTs were compared with yields of top yielding countries.*

CFT Code	CFT Name	Main Crop	LPJmL	Reference value	Reference Source
1	Temperate Cereals	Wheat	14.30	9.59	GYGA, Ethiopia
2	Rice	Rice	15.76	8.21	GYGA, Ethiopia
3	Maize	Maize	12.11	16.44	GYGA, Ethiopia
4	Tropical Cereals	Millet[a]	3.99	5.92	GYGA, Ethiopia
5	Pulses	Beans	8.29	3.38	GYGA, Ethiopia
6	Temperate Roots	Potato	132.77	43.11	FAOSTAT, Netherlands
7	Tropical Roots	Sweet Potato	73.80	21.64	FAOSTAT, China
9	Soybean	Soybean	4.84	3.07	FAOSTAT, Brazil
10	Groundnuts	Groundnut	10.88	10.96	FAOSTAT, Uzbekistan
11	Rapeseed	Rapeseed	7.06	3.86	FAOSTAT, Chile
12	Sugarcane	Sugarcane	79.71	123.68	FAOSTAT, Peru
14	Managed Grass	Grass	192.07	69.05	Schils et al. (2020), Neth.

[a] A reference potential yield for teff, Ethiopia's main tropical cereal, is not available as there are no other countries producing it at large scale aside from Ethiopia. Millet was therefore used as a substitute.

3.3 Precipitation Surplus

We have also evaluated the effect of the different productivity scenarios on the evaporative crop water use (i.e. evapotranspiration, or ET), on irrigation levels, and on precipitation surplus on Ethiopia’s crop area (Figure 3). It should be noted though, that ET and irrigation values depend on CFT productivity values, which at the rainfed and irrigated potential levels were deemed to be over-estimations (Section 2.7.2).The conclusions below should therefore be re-examined after a re-calibration of tuber and grass CFTs. From the results we can conclude the following points:

- For both the driest and wettest climate scenarios, the average annual precipitation is higher in the future scenarios than in the current situation (Table 5).
- Despite the sharp increase in yields at the rainfed potential yields compared to the actual yields (BaU) (Figure 2), there is only a very slight increase in evapotranspiration (ET). This suggests that at the rainfed potential yield level the water use efficiency is much higher. Due to the higher ground coverage by the crops at the rainfed potential, part of the increased transpiration is compensated by a lower evaporation (Table 6).
- The potential yield with limited irrigation causes an increase in annual ET of around 300 mm/yr compared to the ET at the rainfed potential level, which amounts to a relative increase of around 60%. This suggests that water availability is indeed the limiting factor in the rainfed potential scenario, despite the presence of a precipitation surplus. This can be explained by the following points:
    - Given the sharp increase in the yield of grass in the irrigated relative to the rainfed scenario in combination with its large area, it is likely that this CFT dominates the increase in ET. As grass is grown in the more arid regions of Ethiopia, water availability for this CFT is likely a major bottleneck and irrigation leads to both yield and ET increases.
    - It is also likely that the precipitation surplus at the rainfed potential yield cannot be used by the crops in the LPJmL simulation, either because the rainfall takes place outside the simulated growing season or because of rainfall peaks, during which crops cannot make use of all the water and part of it is drained to the ground water.
- Unlimited irrigation leads to an increase in annual irrigation levels of around 500 mm/y compared to limited irrigation, whereas ET levels only increase by around 250 mm/y. This suggests that around half of the extra irrigated water in the unlimited irrigation scenario becomes surface run-off or drains away to the ground water. CFT Managed Grass probably also dominates this response, because no major yield increases were calculated for the arable CFT’s at unlimited irrigation compared to limited irrigation (Figure 2).
- At the limited and unlimited irrigation potential levels the ET is around 60% and 120% higher than at the rainfed potential, whereas average relative yield increases are 28% and 47%. This suggests a much lower water use efficiency at the irrigated potential levels than at the rainfed potential.
- Overall, the results suggests that the increase in yields that could be obtained at the rainfed potential level relative to the actual yield levels (BaU) would not go at the expense of an increased water demand. Irrigated potential yield levels would further increase yields, but at the cost of a much higher water use due to lower water use efficiency.

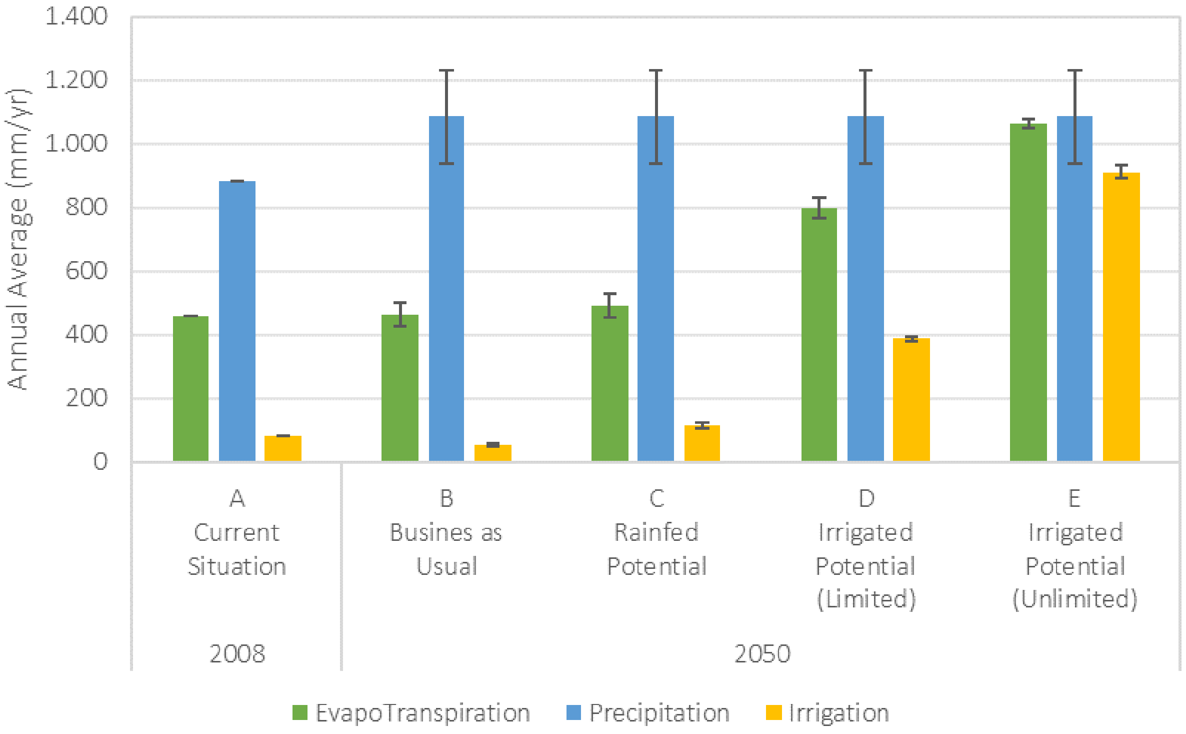

Figure 3 *Average annual evapotranspiration (green) and precipitation (blue) on Ethiopia's total crop area, and annual irrigation (yellow) on Ethiopia's irrigated crop area in scenarios A to E. Irrigated crop area covers 0.56% of total crop area in A, B, and C, and 100% in D and E. Values for the current scenario are averaged across 2000 – 2016 and for the future scenarios from 2036 to 2065. Bars represent values averaged across both climate projections, while error bars represent the difference between the climate projections.*

Table 5 *Average annual precipitation (mm/year) and temperature (°C) in Ethiopia's crop area in the current situation (2000 -2016) (Lange, 2019) and the wet and dry future projections (2036-2065) (ISIMIP3b, 2021).*

	Current	**Dry Projection (GFDL_ESM4)**	**Wet Projection (UKESM1_0_LL)**
Precipitation (mm/yr)	880	934	1230
Temperature (°C)	22.7	23.9	25.1

Table 6 *Average annual evaporation, transpiration, and evapotranspiration (all in mm/year) on Ethiopia's crop area in each scenario.*

Scenario	**Evaporation**	**Transpiration**	**Evapotranspiration**
2008 - Current Situation	94	368	462
2050 - Business as Usual	90	375	466
2050 - Rainfed Potential	34	458	492
2050 - Irrigated Potential (Limited)	37	763	799
2050 - Irrigated Potential (Unlimited)	38	1026	1064

3.4 National Water Discharge

We have also evaluated the effect of the changes in evapotranspiration and irrigation levels in the different scenarios on Ethiopia's national water discharge to its neighbouring countries. For each scenario, we summed all basin in- and outflows across the country, resulting in Ethiopia's net water discharge. However, in the next section, we first evaluate the quality of the basin discharge results as simulated by LPJmL.

3.4.1 Basin Discharge Validation

Monthly historic simulated and recorded discharge values for the Nile, Awash, and Juba-Shibeli basins are reported in Figure 4 for different measuring stations. Overall, the simulated discharge values are in the right order of magnitude, correctly reflecting the difference in size between the Nile and the other two basins. The simulated discharge values also generally follow the seasons correctly, with the peak values in the correct months. However, the simulated discharges generally over-estimate the recorded discharge values. This is in line with the findings of Zaherpour et al. (2018), who conclude that global hydrological models struggle to capture the magnitude of the seasonal cycle. Some reasons for the differences between the measured and simulated values could be the following, not necessarily in order of likelihood:

- A bias in the LPJmL simulation in the partitioning of precipitation between crop ET, storage in the soil, infiltration to ground water and the runoff to surface water. This could be caused by issues in the input data such as soil characteristics and elevation, by the model parameterization, or by the modelling functions.
- The LPJmL simulation covered only one growing season, whereas some cropping areas of Ethiopia have more than one growing seasons (see
- **Table 3**, with harvested areas higher than physical areas). In this version of LPJmL the crop area outside the growing season is simulated as being managed grass. If the ET of grassland is lower than the ET of the crops would be, then this could lead to a lower annual crop ET in the simulation than in reality, causing higher water infiltration levels, and as a result higher water discharge values in the simulation.
- Water removal for human use was not included in the LPJmL simulation, also increasing basin discharge in the simulation compared to reality (Veldkamp et al., 2018). However, the estimated annual water consumption for industrial and domestic purposes (Table 7) suggests that water consumption plays only a small part in the difference between the simulations and the measurements.
- In case of the Nile, the difference might also be caused by ET from the upstream wetland and by evaporation from the river itself, which being so wide presents a considerable area (Nooni et al., 2019), but is not taken into account in the model.
- It is also possible that due to riverbed geology water infiltration takes place in the rivers themselves. This could decrease basin discharge, but is not included in the simulations.
- There can also be uncertainty in the precipitation input data of the simulation. Historic precipitation maps are derived synthetically from point measurements, with topographically complex regions such as Ethiopia leading to high uncertainty levels. This problem in input data quality can lead to biases in basin discharge outcomes (Biemans et al., 2009).

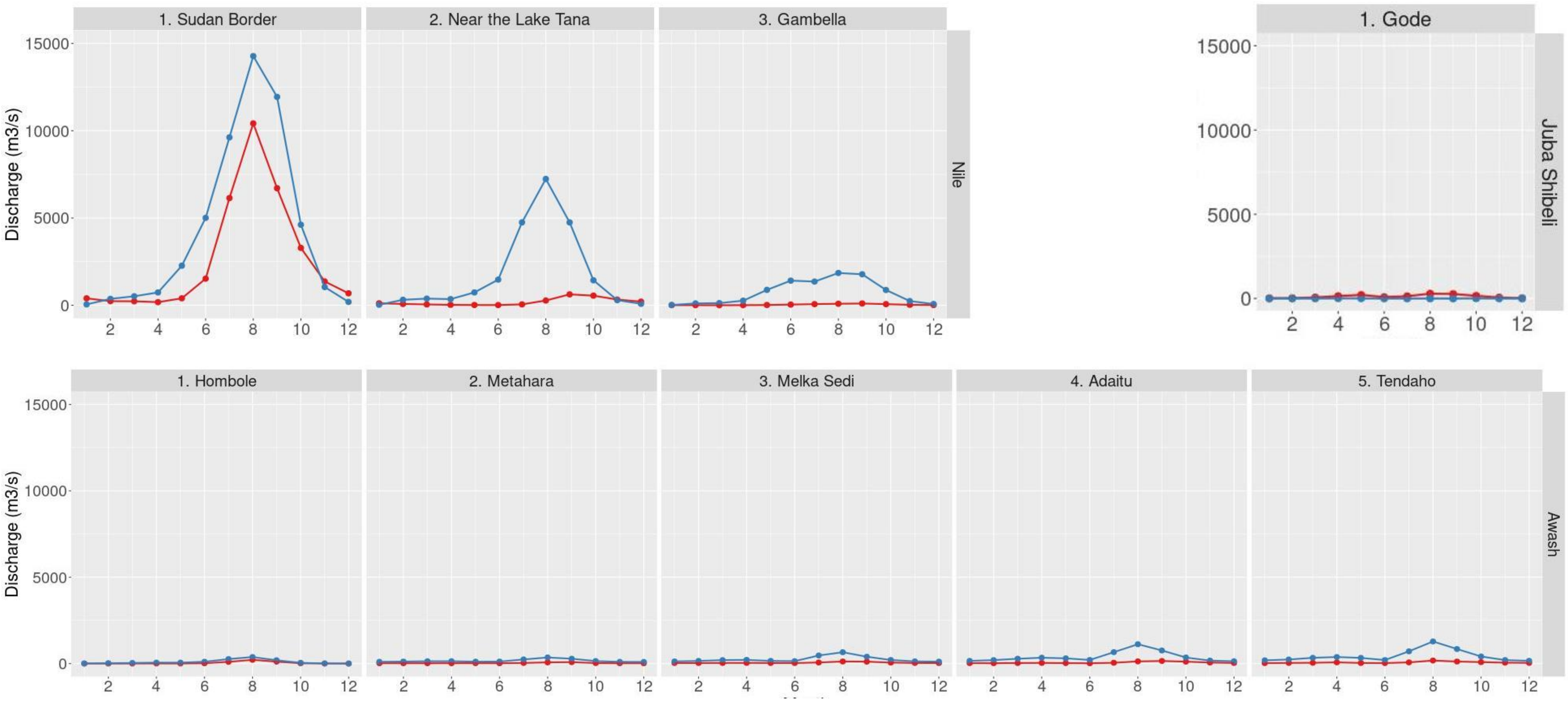

Figure 4 *Average monthly simulated (blue) and measured (red) discharge at discharge measurement stations in the Nile (top left), Juba Shibeli (top right), and Awash (bottom) basins. Averaged years for each station can be found in Table A4 in the Appendix.*

Table 7 *Average industrial and domestic water use in Ethiopia from 2010 to 2019 (AQUASTAT, 2022).*

Consumption type	**Consumption**	
	(10^9 m^3 /year)	**(m^3/s)**
Industrial	0.051	1.6
Domestic	0.810	25.7

3.4.2 National Water Discharge

Ethiopia's national water discharge was estimated for each scenario by adding all incoming and outgoing discharge values across its borders, with the net annual discharges reported in Figure 5. The water discharge of Scenario E, with unlimited irrigation, is not reported as the assumption of more irrigation water than is actually available results in an unrealistic water discharge. Section 3.4.1 has shown that the simulated discharge values, although correct in order of magnitude, tend to overestimate recorded discharge. The net discharges are therefore only informative relative to each other, as their absolute values are likely also an over-estimation. In that light, we can conclude the following points:

- The net discharge in the business as usual (BaU) scenario increases by 54% relative to the current situation because there is an increase in annual precipitation while crop evapotranspiration (ET) remains virtually constant (Section 3.33).
- At the rainfed potential, the slightly higher ET results in a slightly (5%) lower net discharge than in the BaU scenario. However, the increased precipitation still leads to a higher net discharge balance than in the current situation.
- On the other hand, the water balance in the limited irrigation scenario decreases by around 27% and 23% relative to the BaU and rainfed potential scenarios respectively. The irrigation allows for a higher ET, resulting in a higher water loss to the air and a lower net discharge.
- Overall, the results suggest that the increased precipitation in Ethiopia's future projected climate would result in an increased net water discharge to its neighbouring countries compared to the current situation, regardless of the production level. Producing at the rainfed potential would decrease the net water discharge only slightly compared to continued production at the same intensity level (BaU) due to the higher water use efficiency, while widespread irrigation at this production level would decrease the country's net water discharge by almost 30%.

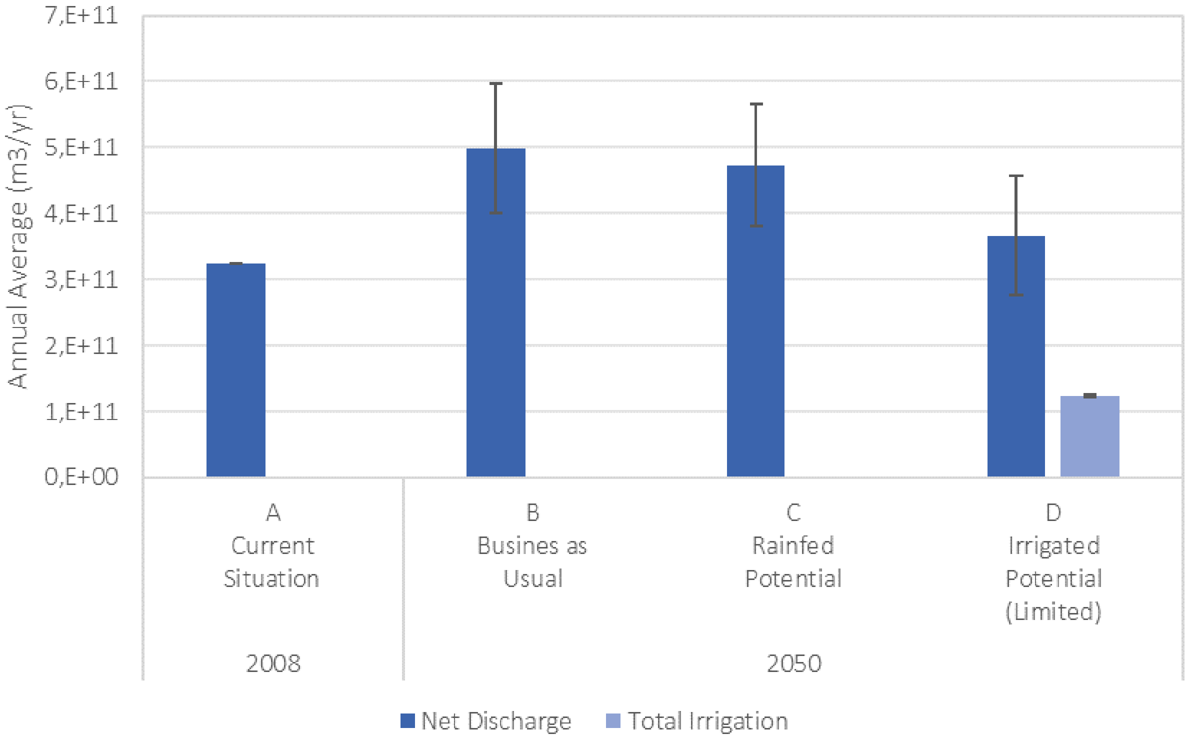

Figure 5 *Net annual discharge from Ethiopia to its surrounding neighbouring countries (dark blue) and total annual irrigation (light blue) in scenarios A to D as simulated by LPJmL. Values for the current scenario are averaged across 2000 – 2016 and for the future scenarios from 2036 to 2065. Bars represent values averaged across both climate projections, while error bars represent the difference between the projections. Scenario E (unlimited irrigation) is not shown as its water discharge is not realistic.*

4 Conclusions and Further Research

4.1 Conclusions

In this study we have explored alternative crop productivity levels in Ethiopia and their impact on food production and on the national water discharge given the country's climate change projections. The following main points can be concluded from the study:

- Average annal crop productivity in Ethiopia's main cropping season is not expected to be strongly affected by the projected changes in Ethiopia's climate up to 2050. Both the driest and wettest climate change projections for the country have an increase in annual rainfall as well as temperature, which for the simulated crops would not lead to yield declines.
- There is a large yield gap between the actual yields and the rainfed potential yields for most simulated crops. The yield gaps between the irrigated and rainfed yield are relatively small, and the gap between limited and unlimited irrigation even smaller (with the exception of Managed Grass with large increases in simulated yields due to their current location in drier regions of Ethiopia). This indicates that water availability is not the main bottleneck for most of the crop production in Ethiopia, but rather crop management. A large increase in crop productivity could likely be achieved without the need for widespread irrigation.
- Increasing yields from the current to their rainfed potential level would not go at the expense of an increased crop water demand due to a higher water use efficiency and a shift in water use from evaporation to transpiration. Crop yields could be increased further through widespread irrigation, but this would increase crop water use considerably.
- The increased precipitation in Ethiopia's future projected climate would result in an increased net water discharge to its neighbouring countries compared to the current situation, regardless of the production level. Producing at the rainfed potential level would decrease the net water discharge only slightly compared to continued production at the current intensity level (BaU) due to the higher water use efficiency, while widespread irrigation at this production level would decrease the country's net water discharge by almost 30%.

4.2 Further Research

To be able to answer the posed research questions further, the following points are suggested for further research:

- The parameterization of LPJmL's CFTs should be further improved, especially for the root crops and grass. This would allow a more accurate prediction of potential yield levels, which were over-estimated in the current study.
- A relevant follow-up study would be to compare the future potential for crop production with the future food demand. This would require modelling a second (and third) growing season as well, in order to estimate annual crop production.
- It should be further examined why LPJmL's basin discharge values differed from the measured basin discharge. This would be necessary to be able to make conclusions on absolute values of the national water discharge.
- It should be further explored what the effect is of the climate projections in individual years and regions of Ethiopia. The values reported in this study are averaged over a period of 30 year and across the whole country, which can average out the effect of localized or temporary droughts.

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Links:

LPJmL Wiki - Grazing: https://github.com/PIK-LPJmL/LPJmL/wiki/Grazing
LPJmL Wiki - Grazing: https://github.com/PIK-LPJmL/LPJmL/wiki/LAI

Annex 1 Supplementary Material

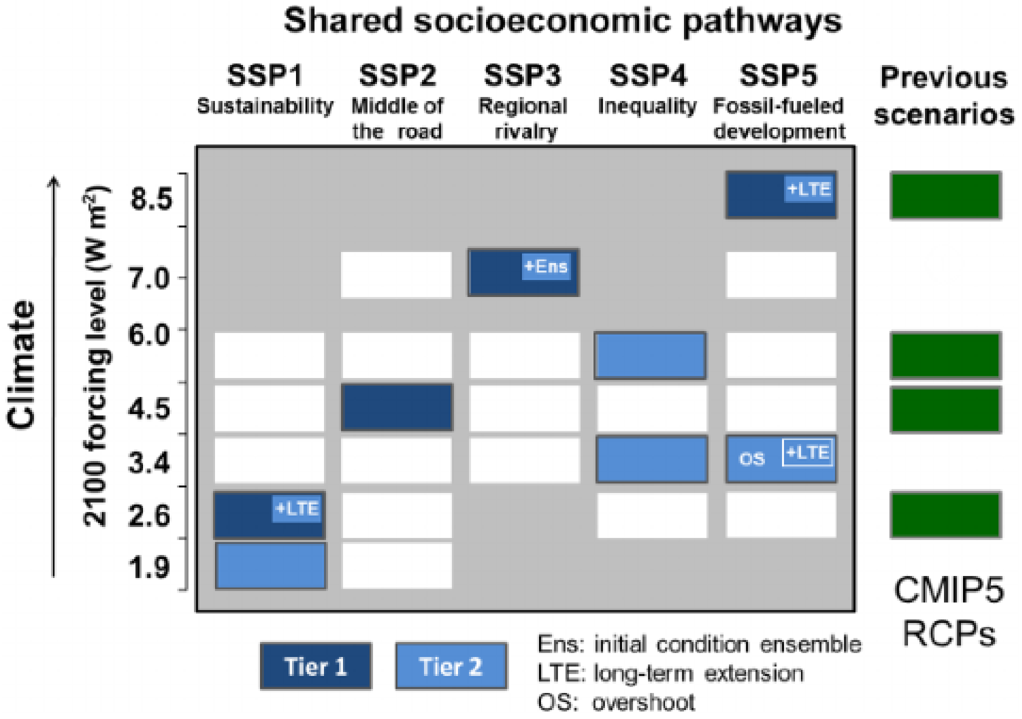

Figure A1 *Matrix of shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs, forcing level). Taken from O'Neill et al. (2016).*

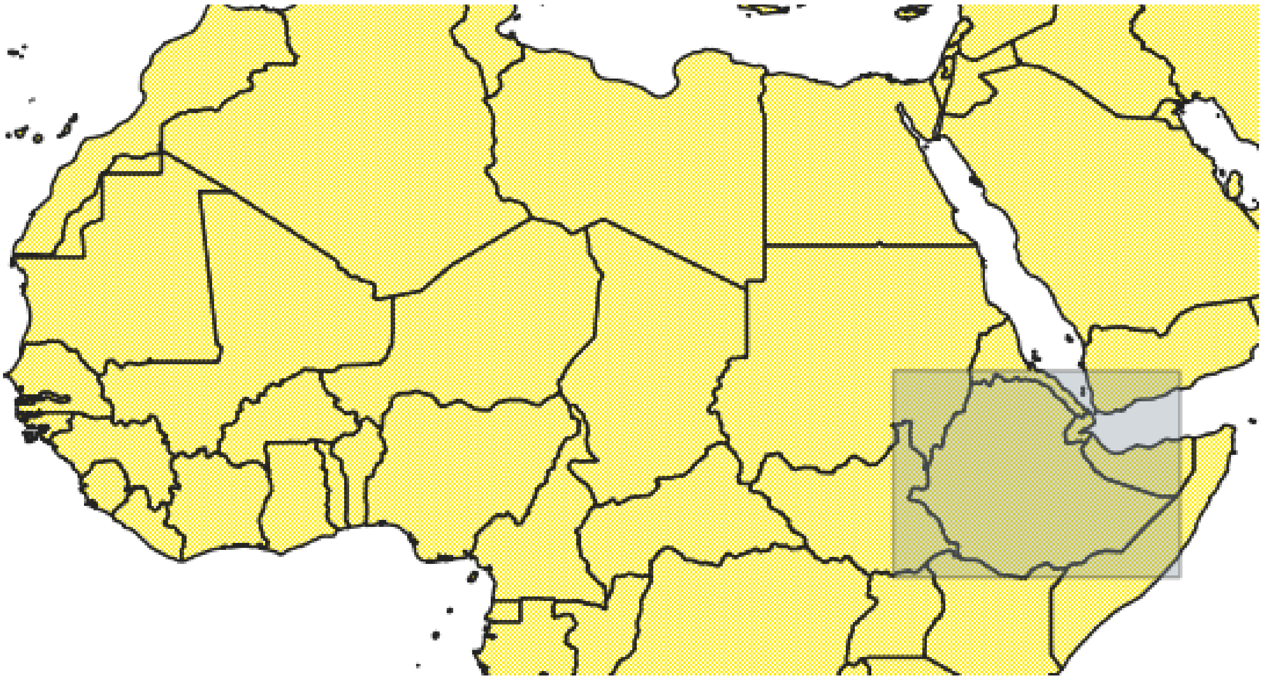

Figure A2 *Area encompassed to calculate average yearly precipitation in climate scenarios (lat: 15° to 3.5°, lon: 32° to 48°). Taken from Hermelink and Conijn (2021).*

Table A1 *Crops in MapSPAM dataset as grouped into crop functional types (CFTs) of LPJmL.*

MapSPAM crop	**Crop Functional Type (CFT) in LPJmL**
wheat	Temperate Cereals
barley	Temperate Cereals
rice	Rice
maize	Maize
pearl millet	Tropical Cereals
small millet	Tropical Cereals
sorghum	Tropical Cereals
other cereals	Tropical Cereals
bean	Pulses
chickpea	Pulses
cowpea	Pulses
pigeon pea	Pulses
lentil	Pulses
other pulses	Pulses
potato	Temperate Roots
sugar beet	Temperate Roots
sweet potato	Tropical Roots
yams	Tropical Roots
cassava	Tropical Roots
other roots	Tropical Roots
sunflower	Sunflower
soybean	Soybean
groundnut	Groundnut
rapeseed	Rapeseed
sugarcane	Sugarcane
coconut	Others
oil palm	Others
sesame seed	Others
other oil crops	Others
cotton	Others
other fibre crops	Others
arabica coffee	Others
robusta coffee	Others
cocoa	Others
tea	Others
tobacco	Others
banana	Others
plantain	Others
tropical fruit	Others
temperate fruit	Others
vegetables	Others
rest of crops	Others

Table A2 *Grouping of crops produced in Ethiopia as reported in FAOSTAT into LPJmL's Crop Functional Types (CFTs). nes = not else specified.*

FAOSTAT crop	CFT	FAOSTAT crop	CFT
Barley	Temperate Cereals	**Maté**	Others
Wheat	Temperate Cereals	**Mustard seed**	Others
Rice, paddy	Rice	**Nutmeg, mace and cardamoms**	Others
Maize	Maize	**Peaches and nectarines**	Others
Cereals nes	Tropical Cereals	**Safflower seed**	Others
Oats	Tropical Cereals	**Sisal**	Others
Millet	Tropical Cereals	**Spices nes**	Others
Sorghum	Tropical Cereals	**Sesame seed**	Others
Beans, dry	Pulses	**Tea**	Others
Chick peas	Pulses	**Tobacco, unmanufactured**	Others
Cow peas, dry	Pulses	**Avocados**	Others
Lentils	Pulses	**Bananas**	Others
Beans, green	Others	**Fruit, citrus nes**	Others
Broad beans, horse beans, dry	Others	**Fruit, fresh nes**	Others
Peas, dry	Pulses	**Fruit, tropical fresh nes**	Others
Peas, green	Other	**Lemons and limes**	Others
Pulses nes	Pulses	**Mangoes, mangosteens, guavas**	Others
Potatoes	Temperate Roots	**Melonseed**	Others
Roots and tubers nes	Tropical Roots	**Oranges**	Others
Sweet potatoes	Tropical Roots	**Papayas**	Others
Yams	Tropical Roots	**Pineapples**	Others
Sunflower seed	Sunflower	**Tangerines, mandarins, clementines, satsumas**	Others
Soybeans	Soybean	**Cabbages and other brassicas**	Others
Groundnuts, with shell	Groundnuts	**Carrots and turnips**	Others
Rapeseed	Rapeseed	**Chillies and peppers, dry**	Others
Sugar cane	Sugarcane	**Chillies and peppers, green**	Others
Coffee, green	Others	**Cucumbers and gherkins**	Others
Seed cotton	Others	**Garlic**	Others
Bastfibres, other	Others	**Leeks, other alliaceous vegetables**	Others
Fibre crops nes	Others	**Lettuce and chicory**	Others
Castor oil seed	Others	**Onions, dry**	Others
Linseed	Others	**Onions, shallots, green**	Others
Nuts nes	Others	**Pepper (piper spp.)**	Others
Oilseeds nes	Others	**Tomatoes**	Others
Anise, badian, fennel, coriander	Others	**Vegetables, fresh nes**	Others
Ginger	Others	**Vegetables, leguminous nes**	Others
Grapes	Others	**Vetches**	Others
Hops	Others		

Table A3 *Dry matter content assumed for the crop functional types (CFTs). Values for the CFTs Sunflower are not reported because the production area in Ethiopia was zero (**Table 2**).*

CFT	Dry Matter Content (gDM/gFM)	Main Crop	Source
Temperate Cereals	0.87	Wheat	GYGA
Rice	0.86	Rice	GYGA
Maize	0.85	Maize	GYGA
Tropical Cereals	0.88	Teff	Feedipedia (2020)
Pulses	0.89	Beans	Feedipedia (2020)
Temperate Roots	0.21	Potato	GYGA
Tropical Roots	0.27	Sweet Potato	Feedipedia (2020)
Sunflower	-	-	-
Soybean	0.89	Soybean	GYGA
Groundnuts	0.93	Groundnut	Mrema et al. (2012)
Rapeseed	0.92	Rapeseed	Feedipedia (2020)
Sugarcane	0.25	Sugarcane	GYGA
Managed Grass	0.32	Grass	(Feedipedia, 2020)

Table A4 *Start and end year of discharge measurements at each analysed measuring station (GRDC, 2022).*

Basin	Measuring Station	Start Year	End Year
Nile	Sudan Border	1969	1975
	Lake Tana	1969	1975
	Gambella	1928	1979
Juba Shibeli	Gode	1969	1975
Awash	Hombole	1990	2009
	Metahara	1982	2009
	Melka Sedi	1990	2009
	Adaitu	1990	2004

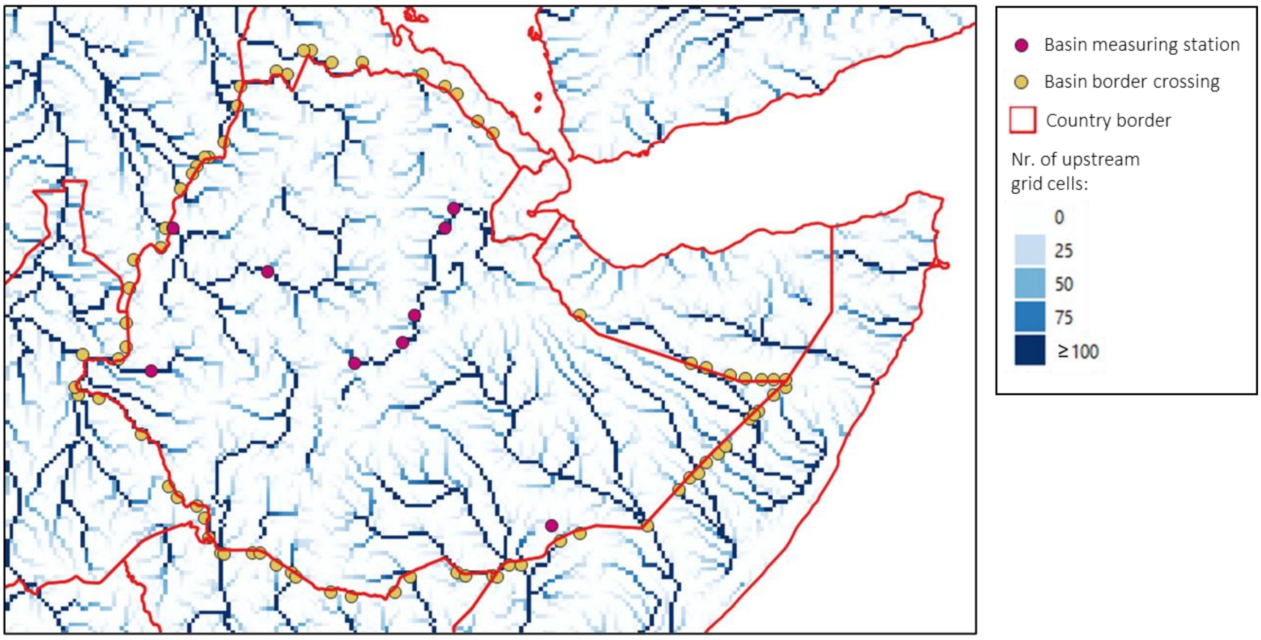

Figure A3 *Basin discharge measuring stations (pink points) and border crossings (yellow points) on the HydroSheds river network (Lehner et al., 2008). Measuring stations obtained from the GRDC (2022).*

Corresponding address for this report:
P.O. Box 16
6700 AA Wageningen
The Netherlands
T +31 (0)317 48 07 00
wur.eu/plant-research

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The Netherlands
T +31 (0) 317 48 07 00
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