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ORIGINAL ARTICLE

Can the cropping systems of the Nile basin be adapted to climate change?

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Abstract

Climate change poses a fundamental threat to agriculture within the Nile basin due to the magnitude of projected impacts and low adaptive capacity. So far, climate change impacts on agriculture for the basin have mostly been assessed for single-cropping systems, which may bias the results considering that the basin is dominated by different cropping systems, with about one-third of the crop area under double cropping. In this study, we simulate single- and double-cropping systems in the Nile basin and assess the climate change impacts on different cropping systems under two scenarios, i.e. “no adaptation” and “adaptation to a late-maturing cultivar”. We find that the mean crop yields of maize, soybean and wheat decrease with future warming without cultivar adaptation. We attribute this to the shortening of the growing season due to increased temperature. The decrease is stronger in all single-cropping systems (12.6–45.5%) than in double-cropping systems (5.9–26.6%). The relative magnitude of yield reduction varies spatially with the greatest reduction in the northern part of the basin experiencing the strongest warming. In a scenario with cultivar adaptation, mean crop yields show a stronger increase in double-cropping systems (14.4–35.2%) than single-cropping systems (8.3–13.7%). In this scenario, farmers could possibly benefit from increasing cropping intensities while adapting to late-maturing cultivars. This study underscores the importance of accounting for multiple-cropping systems in agricultural assessments under climate change within the Nile basin.

Keywords Climate change · Agriculture · Multiple cropping · Adaptation · Nile basin

Introduction

Agriculture is the backbone of the economy and food security in all Nile basin countries, with the sector playing a central role in supporting rural livelihoods and strengthening of regional integration through trade in agricultural products (Ahmed 2021a). At the same time, agriculture is threatened by climate change, which is one of the biggest challenges to the world in present times (Malhi et al. 2021). According to the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC; Pörtner et al. 2022) and Pequeno et al. (2021), the vulnerability of agriculture to climate change is overwhelmingly high in developing regions such as the Nile basin that depend on agriculture as the main source of livelihoods (Awulachew et al. 2010; Kassie et al. 2014; Coffel et al. 2019). Moreover, the majority of agricultural systems in the Nile basin is rainfed with only about 20–25% irrigated (Senay et al. 2014; Multsch et al. 2017), hence directly affected by the unpredictable precipitation and temperature variations. Even though there is ample evidence that agricultural systems will be reshaped under climate change (Meza and Silva 2009), the degree of climate change impacts on agricultural production differs between crops, crop cultivars (Abera et al. 2018; Elbeltagi et al. 2020) and between cropping systems (Thornton et al. 2010; Waha et al. 2013).

The Nile basin has both single- and multiple-cropping systems due to tropical and subtropical climate. By multiple-cropping systems in this study, we mean a cropping system with two crops grown in sequence on the same piece of land

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within 12 months (Waha et al. 2013). Unlike single-cropping systems, multiple-cropping systems are often unaccounted for in assessments of global and regional food production (Waha et al. 2020a). Subsequently, the representation and impact of multiple-cropping systems are neglected in most regional to global agricultural and eco-hydrological models (Nkwasa et al. 2022a). However, with climate change likely to cause a change in the length of growing season due to variations in temperature and precipitation (Thomas 2020), focusing only on crop yield responses without evaluation of different cropping systems leads to relevant inaccuracies when assessing the impact of climate change on agriculture (Iizumi and Ramankutty 2015).

The impacts of climate change on agricultural production in the Nile basin at both local and regional scale have mostly been estimated by simulating a single crop in the field per year (Kassie et al. 2015; Kikoyo and Nobert 2016; Abera et al. 2018; Kassaye et al. 2021; Ginbo 2022). A significant knowledge gap, therefore, exists around the impacts of climate change on different cropping systems in the basin, which is a basis for exploring the scope of sustainability of agricultural systems against climate change. In sub-Saharan Africa (SSA), a few studies have already shown that different cropping systems are impacted differently by climate change (Thornton et al. 2009; Waha et al. 2013; Duku et al. 2018). Understanding the impact of climate change on different cropping systems in the Nile basin could be key in informing how the basin can adapt and respond to a changing climate, in turn reducing the pressures on agricultural production. For instance, whether yields are more likely to be reduced in the single-cropping systems or the multiple-cropping systems could be critical for informing priority investments that focus on adaptation to a specific cropping system relative to the many other potential uses of scarce resources for agricultural development.

Adaptation will have to be a priority for climate policy to reduce exposure and vulnerability to climate change on agriculture (Adenle et al. 2017; Pörtner et al. 2022), especially in African agricultural ecosystems where vulnerability is high due to low adaptive capacity (Hassan and Nhemachena 2008). Some studies in SSA (Bryan et al. 2009, 2013; Hisali et al. 2011; Fosu-Mensah et al. 2012; Akinyi et al. 2021; Pequeno et al. 2021) have shown that without adaptation strategies, future warming will most likely be detrimental to agriculture, but can partly be offset by several adaptation strategies. However, climate change is likely starting to outstrip local agricultural adaptation efforts in parts of Africa (Rippke et al., 2016). For example, in the Nile basin, Iizumi et al. (2021) show that Sudan's domestic production share may decrease from 16 to 4.5–12.2% by 2050 despite the use of adjusted sowing dates and existing heat-tolerant varieties. Hence, to keep up the pace with climate change, more research is needed into the adaptation options for agriculture in the basin. More precisely, adaptation assessments that incorporate different cropping systems are needed to draw regional conclusions on the overall adaptation potential and prioritization within the agricultural sector.

This study aims to assess the impact of climate change on crop yields in different cropping systems in the Nile basin under two scenarios, i.e. "no adaptation" and "adaptation to a late-maturing cultivar". In this framework, we simulate single- and double-cropping systems in the Nile basin from a new multiple-cropping dataset (Waha et al. 2020b), using a regionally calibrated Soil and Water Assessment Tool (SWAT+) model for the Nile basin (Nkwasa et al. 2022b) and the recent future emission scenarios of the Coupled Model Inter-comparison Projects 6 (CMIP6; Eyring et al. 2016; Meinshausen et al. 2020). The two scenarios are simulated to explore the benefits of cultivar adaptation for different cropping systems under future climate conditions.

Materials and methods

Study area

The Nile basin located in the Northeast part of Africa (Fig. 1a) is about 3,489,000 km^2. This area covers fully or partially eleven countries including Kenya, Tanzania, Uganda, Burundi, Rwanda, Ethiopia, Egypt, Eritrea, Democratic Republic of Congo, Sudan and South Sudan. The distribution of the average annual rainfall in the basin is spatially contrasted in the region with about 28% of the Nile basin receiving less than 100 mm yea^{-1}. Rainfall in excess of 1000 mm yea^{-1} is limited mainly to the equatorial region and the Ethiopian highlands, with negligible rainfall (less than 50 mm yea^{-1}) from northern Sudan all across Egypt (Onyutha and Willems 2015).

The agricultural sector is responsible for approximately 75% of the water withdraw within the basin (Swain, 2011), extracted from surface water and groundwater storages (Wada et al. 2014). Agriculture is practiced predominantly in the low-lying areas with altitude less than 500 m and medium areas with altitude between 890 and 1450 m. Rainfed agriculture is the dominant farming scheme in the basin. However, regional irrigated areas are projected to increase by 41% by 2050 with in the basin (Multsch et al. 2017).

Three catchments (Fig. 1b) from different climatic zones within the Nile basin were selected as representative catchments to investigate the local impacts of climate change on crop yields from different cropping systems in different climatic zones. In the Upper Blue Nile catchment, there is predominantly one rainy season (June—September). The rainfall in the Victoria catchment exhibits a bimodal pattern with two rainy seasons (March–May and October–December) while the Nile delta is mostly dry with mainly irrigated

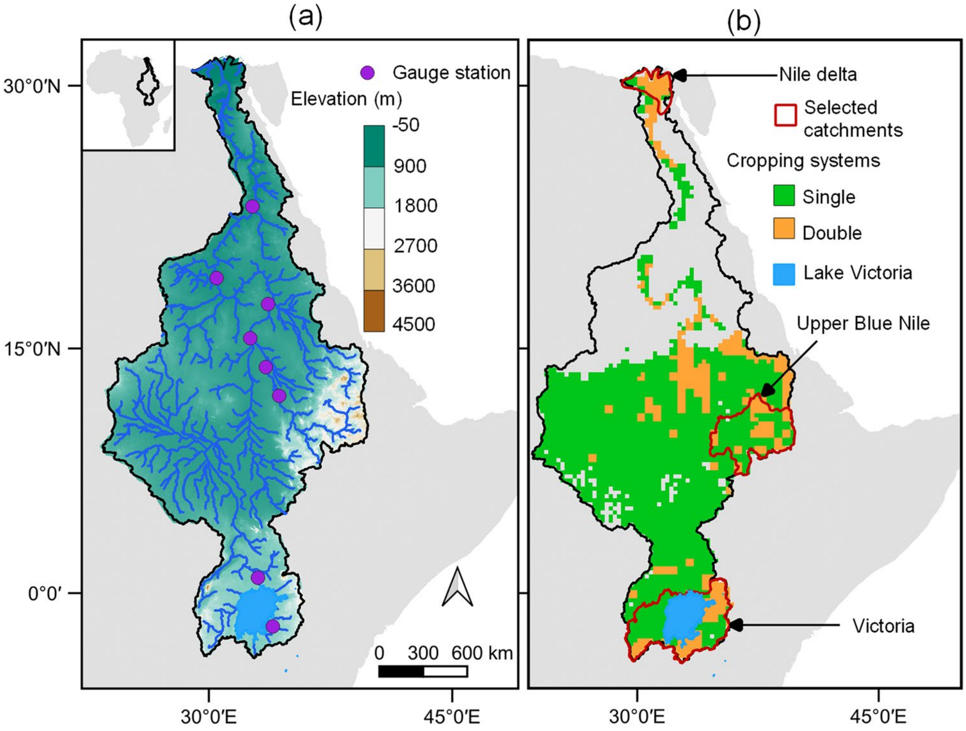


Fig. 1 Study area. **a** Elevation in the Nile basin and location of flow gauge stations. **b** Nile basin with single- and double-cropping areas extracted from Waha et al. (2020b) and the three selected local catchments in the basin

cropping in the two main growing seasons from May–September and October–April. The rainy season represents the major cropping seasons in the Nile basin as rainfall is the primary controlling factor for crop growth dynamics in the tropics and sub-tropics (Msigwa et al. 2022; Nkwasa et al. 2022a).

Input data

Cropping systems and observed data

We used the harmonized land use map (LUH2; Hurtt et al. 2020) at 0.25° resolution, a digital elevation model (DEM; Farr et al. 2007) at 90-m horizontal resolution, a soil map from the Africa Soil Information Service (AfSIS; Hengl et al. 2015) at 250-m resolution, a map of irrigated areas from FAO (Siebert et al. 2013) at 0.083° resolution, crop phenology data set with multiple-cropping systems (Waha et al. 2020a, b) at 0.5° resolution and elemental nitrogen and phosphorus fertilizer maps (Lu and Tian 2017; Hurtt et al. 2020) at 0.5° resolution. We use data on daily precipitation, minimum and maximum temperature, solar radiation, humidity and wind speed at 0.5° resolution from the global observational dataset GSWP3-W5E5, which is a merge between the GSWP3 (Global Soil Wetness Projected phase 3) data set (Dirmeyer et al. 2006; Kim 2017) and the W5E5 dataset (Lange 2019a; Cucchi et al. 2020).

Crop phenology data with different cropping systems (Fig. 1b) and crop management practices of fertilization and irrigation were incorporated in the model using decision tables (Nkwasa et al. 2020, 2022a). Decision tables are a precise way to model rule sets and the corresponding actions by allowing a user to add conditions for scheduling management in the model (Arnold et al. 2018). We simulate three crops: maize, wheat and soybean. The choice of the three crops represents the basin land use well with wheat, maize and soybean being amongst the major C3 annual, C4 annual and C3 nitrogen fixing crops in the basin (Adhikari et al. 2015; Nkwasa et al. 2022a). In the double-cropping areas (Fig. 1b), each crop was simulated sequentially as a double-cropping system and the crop yield subsequently calculated as the sum of the yield from the two cropping seasons. Hence, the double-cropping systems implemented in this study are maize–maize, wheat–wheat and soybean–soybean, selected based on previous studies (Waha et al. 2020a). The double-cropping systems were either entirely rainfed for rainfed areas or entirely irrigated for irrigated areas. For regions with fertilizer application, a constant annual fertilizer amount (Lu and Tian 2017; Hurtt et al. 2020) was applied throughout the simulations.

GCM historical and future climate data

We used daily precipitation, minimum and maximum temperature, solar radiation, humidity and wind speed at 0.5° resolution for the historical period 1970 to 2000 and for the future period 2071 to 2100 from 5 GCMs (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and

UKESM1-0-LL) of the bias-corrected CMIP6 climate forcing data (Lange 2019a, b; Lange et al. 2021) under the SSP5-RCP8.5 scenario. The five GCMs were selected to show the possible future temperature (Table 1) and precipitation patterns (Fig. 2) under the SSP5-RCP8.5 scenario that represents the high end of plausible future pathways.

The selected GCMs mostly project an increase in precipitation (Fig. 2) within the region especially in the Ethiopian highlands, which represents the CMIP6 mean model ensemble under the SSP5-RCP8.5 scenario (Almazroui et al. 2020). Additionally, we used the atmospheric CO_2 composition data for SSP5-RCP8.5 (Büchner and Reyer 2020). However, since SWAT + does not allow incremental increases of CO_2 concentration, the historical annual average (i.e. 350 ppm) and future annual average (i.e. 950 ppm) values were used.

SWAT + model

SWAT + is a revised version of the Soil Water and Assessment Tool (SWAT) model (Arnold et al. 1998), with enhanced capabilities in terms of spatial representation

Table 1 Projected future change in temperature after bias correction for selected Global Climate Models GCMs

Projected change in temperature (SSP5-RCP8.5)	Selected GCMs				
	MPI-ESM1-2-HR	GFDL-ESM4	MRI-ESM2-0	IPSL-CM6A-LR	UKESM1-0-LL
Mean global change (Lange 2020) (°C)	~3.0	~3.0	3.5–4.0	4.5–5.0	> 5.5
Mean change in the Nile basin (°C)	3.2	3.6	4.1	5.4	6.3

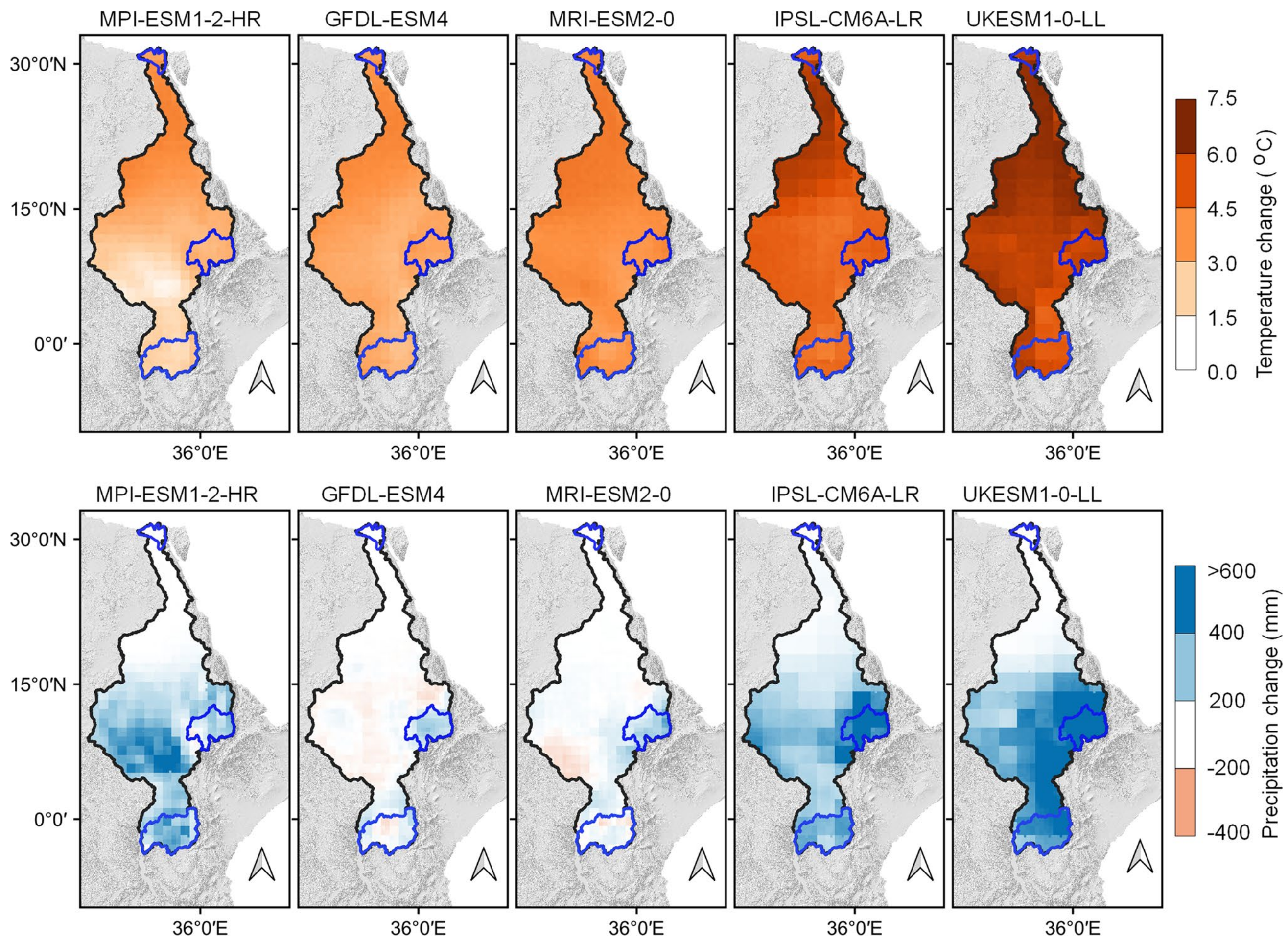


Fig. 2 Change in annual mean temperature and annual mean precipitation in the Nile basin from periods 1971–2000 to 2070–2100 projected from selected five Global Climate Models (GCMs) under Coupled Model Intercomparison Project Phase 6 (CMIP6)

of objects (e.g. channels, aquifers, ponds, reservoirs, etc.) and processes in watersheds (Arnold et al. 2018; Bieger et al. 2017). The model offers more flexibility than SWAT in defining routing constituents, management schedules and connecting managed flow systems to the natural river network (Bieger et al. 2017). In SWAT +, a watershed is divided into sub-watersheds connected by a stream network, which are further divided into hydrologic response units (HRUs). HRUs are homogeneous spatial units characterized by unique properties of land use, soil, slope class and management practices (Neitsch et al. 2005).

The SWAT + model was initially set up and run from 1970 to 2012 using this period for hydrological calibration and calibration of crop yield, before running the climate change scenarios. The Nile basin was discretized into 63,622 HRUs, each between 0.85 km^2 and 729 km^2 large. The Victoria, Upper Blue Nile and Nile delta catchments consists of 4218, 2325 and 310 HRUs respectively.

Phenological development and cultivar adaptation

Plant growth is simulated at the HRU level using the simplified version of the EPIC growth model (Neitsch et al. 2005). Management operations that control the plant growth cycle, timing of fertilizer, irrigation application and removal of plant biomass can be scheduled through either calendar days or heat units (Neitsch et al. 2005). The model utilizes the concept of days to maturity, which enables the user to include different crop cultivars as defined by the length of growing season (LGS). The model sums heat units for the entire growing season which represents the maximum amount of heat units.

Table 2 Default base and optimal temperatures for selected crops in this study (Liu et al. 2008; Arnold et al. 2013; Sinclair et al. 2014)

Crop	Base temperature (°C)	Optimal temperature (°C)
Maize	8.0	25.0
Wheat	0.0	18.0
Soybean	10.0	25.0

We simulate two scenarios for phenological crop development, scenario A without any cultivar adaptation and scenario B with cultivar adaptation under future climate. For scenario A, we calculate the potential heat units (PHUs) of each crop from historical climate data (1970–2000) using the observed plant and harvest days (Waha et al. 2020b) and base temperatures in Table 2 for each GCM. PHUs are calculated using Eqs. (1) and (2).

$$\mathrm{PHU} = \sum_{d=1}^{h} \mathrm{HU} \tag{1}$$

$$\mathrm{HU} = \mathrm{T_m} - \mathrm{T_{base}}\,\mathrm{when}\,\mathrm{T_m} > \mathrm{T_{base}} \tag{2}$$

where “HU” is the number of heat units accumulated on a given day, “d” where “d = 1” is the first day of planting and “h” is the number of days to maturity. “$\mathrm{T_m}$” is the mean daily temperature (°C) and “$\mathrm{T_{base}}$” is the plant’s base temperature for growth (°C).

As the model simulates harvest to occur after a certain number of days after planting, we calculate the number of days from planting to harvest with future climate so that the same PHUs as with current climate are reached. Table 3 shows this adjusted LGS for scenario A. As temperatures increase, the crop matures earlier if PHUs are kept constant. For scenario B, we assume that farmers switch to a late-maturing cultivar. To simulate this, we maintain the same LGS as calculated for the current climate (Table 3). All the other management practices (fertilization and irrigation) are kept constant in both scenario A and B. In total, we run 15 simulations with GCM forcing (i.e. 1 historical scenario × 2 crop cultivar scenarios × 5 GCMs).

Table 3 Estimated length of the growing season (LGS) in days for different climate scenarios and both cultivar adaptation scenarios

Cropping season and crop	Simulated historical LGS^{a,b} (1971–2000)	Simulated future LGS (2071–2100) without cultivar adaptation				
		MPI-ESM1-2-HR	GFDL-ESM4	MRI-ESM2-0	IPSL-CM6A-LR	UKESM1-0-LL
Single maize	114 ± 10	94 ± 9	86 ± 8	82 ± 7	75 ± 7	75 ± 7
Single wheat	120 ± 15	105 ± 14	99 ± 13	98 ± 14	92 ± 11	90 ± 15
Single soybean	118 ± 13	102 ± 15	91 ± 15	88 ± 14	81 ± 14	78 ± 14
Double maize	107 ± 13	90 ± 10	82 ± 10	77 ± 11	70 ± 9	70 ± 9
Double wheat	110 ± 12	96 ± 13	93 ± 13	91 ± 11	85 ± 10	83 ± 10
Double soybean	104 ± 11	90 ± 14	79 ± 17	78 ± 15	72 ± 13	68 ± 13

[a] LGS from observed growing season length dataset (Waha et al. 2020b)

[b] The same LGS is applied across the 5 GCMs

Biomass accumulation

In this study, plant growth is simulated under actual conditions with temperature, water, nitrogen and phosphorus nutrient stresses (Neitsch et al. 2005; Arnold et al. 2012). SWAT + simulates actual plant growth by applying an actual plant growth factor that includes the stress factors according to the plant stress algorithms (Neitsch et al. 2005). The plant growth factor (γ_r) calculated in Eq. (3) quantifies the fraction of potential growth realized on a given day.

$$\gamma_r = 1 - \mathrm{MAX}(\mathrm{wstrs}, \mathrm{tstrs}, \mathrm{nstrs}, \mathrm{pstrs}) \tag{3}$$

where "MAX" is a mathematical function that returns the maximum value of an array, "wstrs" is the water stress, "tstrs" is the temperature stress, "nstrs" is the nitrogen stress and "pstrs" is the phosphorus stress. The stress factor equations are described in Supplementary Material A. The plant growth factor ranges from 0.0 to 1.0. In the presence of any stress, the plant growth factor is greater than 0.0 and the daily biomass accumulation, Eq. (4) is adjusted.

$$\Delta\mathrm{bio}_{\mathrm{act}} = \left\{0.5\mathrm{xI_d xRUEx}\left[1 - \exp\left(-\mathrm{k_j xLD}\right)\right]\right\}\mathrm{x}\gamma_{\mathrm{r}} \tag{4}$$

$$\mathrm{bio} = \sum_{i=1}^{d} \Delta\mathrm{bio}_{\mathrm{act}} \tag{5}$$

where "$\mathrm{I_d}$" is the photosynthetically active radiation, "$\mathrm{k_j}$" is the light interception, "LD" is the Leaf Area Index (LAI) development, "RUE" is the radiation use efficiency, "$\Delta\mathrm{bio}_{\mathrm{act}}$" is the actual increase in daily plant biomass adjusted for stress on a given day and "bio" is the total plant biomass on a given day (d). Using the plant biomass, Eq. (5) and the potential harvest index, "HI", the crop yield is calculated using Eqs. (6) and (7).

$$\mathrm{yld} = \mathrm{bio_{agg}xHI}\ \text{ for HI} \leq 1.0 \tag{6}$$

$$\mathrm{yld} = \mathrm{bio}\left[1 - \frac{1}{(\mathrm{HI}+1)}\right]\ \text{ for HI} > 1.0 \tag{7}$$

where "yld" is the crop yield and "$\mathrm{bio_{agg}}$" is the above ground biomass on harvest day.

The influence of atmospheric CO_2 concentrations

SWAT + considers the adjustment in biomass production due to changes in CO_2 concentration in two ways. The first way being the direct influence on the radiation use efficiency (Eq. (8)).

$$\mathrm{RUE} = \frac{100\mathrm{CO_2}}{\mathrm{CO_2} + \exp(\mathrm{r_1} - \mathrm{r_2xCO_2})} \tag{8}$$

where "CO_2" is the concentration of carbon dioxide in the atmosphere and "r_1"and "r_2" are shape coefficients.

Additionally, by modifying the canopy resistance when using the Penman–Monteith equation to calculate ET, the impact of CO_2 change due to modified plant-water productivity is considered (Wang et al. 2017). The Penman–Monteith equation combines terms that account for energy to sustain evaporation, strength of the mechanism required to remove water vapour and aerodynamic and canopy resistance (Neitsch et al. 2005). The CO_2 effect on canopy resistance, "r_c" is calculated (Eq. 9) using the proposed equation (Easterling et al. 1992).

$$\mathrm{r_c} = \frac{\mathrm{r_a}}{(0.5\mathrm{xLD})\mathrm{x}(1.4 - 0.4\mathrm{x}\frac{\mathrm{CO_2}}{330})} \tag{9}$$

where "r_a" is the minimum effective stomatal resistance of a single leaf. An increase in stomata resistance or reduced stomatal conductance leads to a decrease in evapotranspiration (ET). Experimental evidence and research shows that C3 plants grow faster and larger with reduced water use than C4 plants under increased CO_2 concentrations (Rosenberg et al. 1999; Ficklin et al. 2009).

Irrigation scheduling in SWAT +

In irrigated agricultural HRUs, irrigation can be scheduled as individual predefined events or automatically by the model in response to a water deficit in the soil (Neitsch et al. 2005). If scheduled automatically by the model, irrigation water is applied any day when the total soil water in the profile falls below field capacity by more than the soil water deficit threshold. Since actual field irrigation is commonly scheduled in response to soil water content in the plant rooting zone, this method has been reported to closely represent field management practices (Chen et al. 2017). Due to the lack of exact data about irrigation timing and amount for each irrigated HRU, the irrigation in this study area was triggered by a soil water deficit threshold. In irrigated agricultural HRUs, the soil water deficit threshold was defined as 75% of the soil field capacity and a maximum irrigation amount of 50 mm per irrigation event was specified.

Model calibration

Hydrological calibration

Hydrological calibration of the default SWAT + model was done using the Hydrological Mass Balance Calibration (HMBC; Chawanda et al. 2020) approach, mostly from 1970 until 1996. ET data from WaPOR (https://wapor.apps.fao.org) at 250-m resolution and observed discharge data obtained from Global Runoff Data Centre (GRDC; http://

grdc.bafg.de) were used during the HMBC. The HMBC and evaluation of this study area is covered in Nkwasa et al. (2022b) and briefly discussed in Supplementary Material B.

Crop yield calibration

Annual observed historical (1980–2012) grain yield data (t/ha) for three crops (maize, wheat and soybean) in this study was extracted from the FAO database (https://www.fao.org/faostat/en/#data) for all the Nile basin countries and used in the calibration and validation process (Supplementary Material C). Several previous studies have recommended the evaluation of SWAT crop yields using the long-term average due to the difficulties in capturing annual variations (Srinivasan et al. 2010; Epelde et al. 2015). Hence, the validation was carried out for the 1980–2012 mean crop yields (Supplementary Material C).

Leaf Area Index (LAI) validation

Remote sensing LAI from Copernicus Global Land Service (CGLS; https://land.copernicus.vgt.vito.be/) at 1-km resolution was compared with LAI simulated from the model for the simulated period to assess the representation of the crop phenology for different cropping systems (Supplementary Material D). The model simulated vegetative temporal dynamics (LAI seasonal trends) of agricultural HRUs was compared to the temporal dynamics from remote sensing for the selected catchments (Fig. 1b) in the Nile basin.

Quantification of uncertainty

Quantifying the uncertainty in modelling results helps to improve the understanding of the projected effects of climate change which could inform decision-making in adaptation planning. The standard deviation of the GCM spread in modelling results was calculated to represent the uncertainty in modelling results. The choice of representing this uncertainty without a robust uncertainty analysis was based on the reported higher contributions of uncertainty from GCMs than crop and hydrological models under climate change (Her et al. 2019; Zhang et al. 2019).

Results

Climate change impact on crop yields

A detailed analysis of changes in yields for the individual crops (Fig. 3) shows that mean maize, soybean and wheat yields in the Nile basin decrease in scenario A by 8.9 ± 2.7%, 13.6 ± 3.1% and 35.8 ± 3.7%, respectively. However, in scenario B, maize and soybean yields increase by 28.7 ± 3.7% and 33.6 ± 5.1% respectively while wheat yields still decrease by 19.39 ± 4.8% at the Nile basin scale. In scenario A, the maize and soybean yields decrease by 17.5 ± 1.9% and 8.4 ± 2.1%, respectively in the Victoria catchment but increase by 2.4 ± 1.6% and decrease by 9.4 ± 3.1% respectively in the Upper Blue Nile catchment. In scenario B, the maize and soybean yields increase by 20.8 ± 2.2% and 30.3 ± 3.4% respectively in the Victoria catchment and by 48.3 ± 6.3% and 44.9 ± 5.8% respectively in the Upper Blue Nile. Wheat yields decrease between 8.8 ± 1.9 and 53.2 ± 6.1% in both cultivar scenarios across the three local catchments. Wheat has the lowest base and optimal temperatures of all crops and its phenological development is most likely to be negatively impacted by increases in temperatures. Our simulation results suggest that at the local

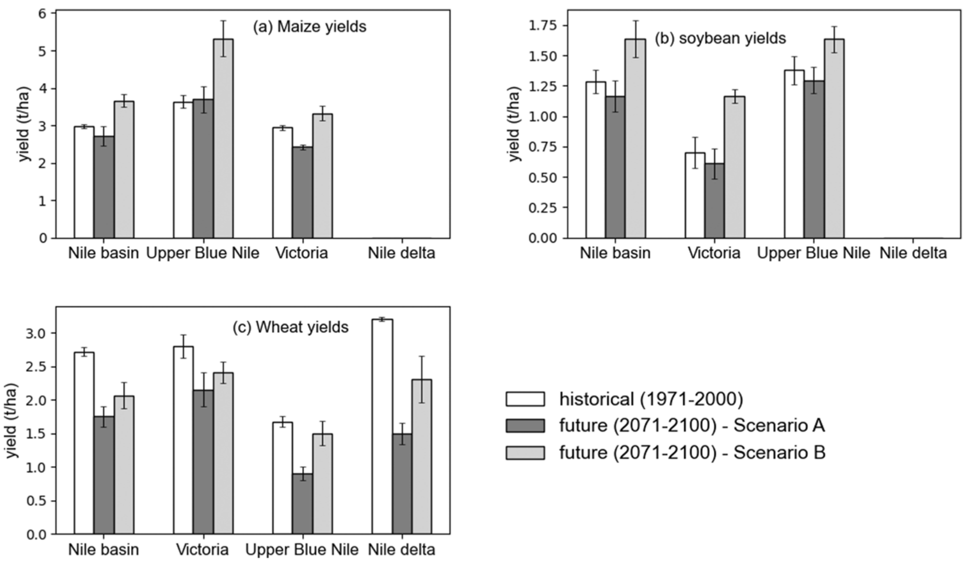


Fig. 3 Mean crop yields for maize, soybean and wheat in the Nile basin and selected local catchments for historical period (1971–2000) and projected period (2071–2100). Scenario A represents a setup without any cultivar adaptation and scenario B is a setup with adaptation to a late-maturing cultivar

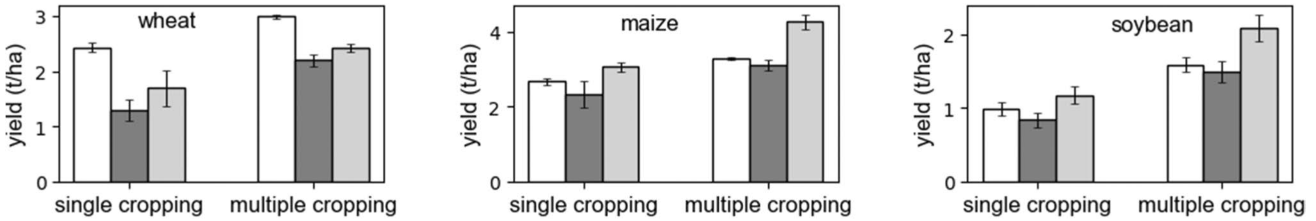
scale, yield reductions are strongest in the Nile delta which is due to stronger local warming than in the other catchments (Fig. 2).

Climate change impacts by cropping system

Crop yields from HRUs (plot areas) with a single-cropping system are compared with crop yields from HRUs with double-cropping systems. Overall, mean crop yields (Fig. 4) in the Nile basin and in the individual catchments are higher in double-cropping systems compared to single-cropping systems. Typically, crop yield decreases with climate change in scenario A without cultivar adaptation and increases in scenario B with cultivar adaptation (Fig. 4). This is irrespective of the catchment or the cropping system, except for the Upper Blue Nile catchment where yields in double-cropping systems increase in both scenarios, also without cultivar adaptation. A closer look at the changes in yields of individual crops (Fig. 4) shows that the mean crop yield reduction is greater in single-cropping systems (12.6 ± 2.1–46.5 ± 7.4%) than in the double-cropping systems (5.9 ± 1.6–26.6 ± 5.3%) in scenario A within the Nile basin. A similar trend is observed at the local catchment level. In scenario B, the maize and soybean mean crop yield in the double-cropping systems (14.4 ± 6.9–35.2 ± 9.1%) is higher than in the single-cropping systems (8.3 ± 6.3–13.7 ± 5.9%) in the Nile basin with a similar pattern at the local level in Victoria and Upper Blue Nile catchments.

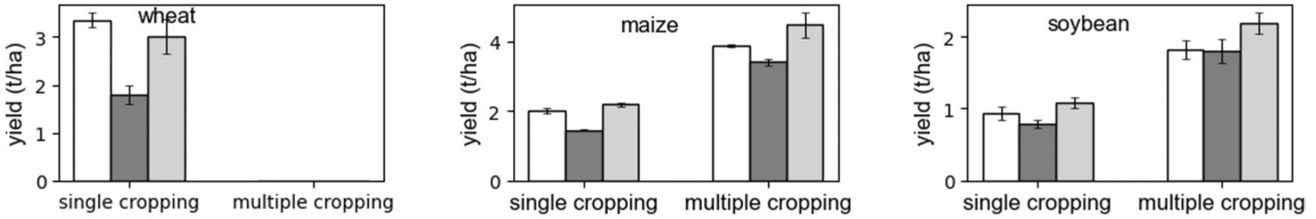
On the contrary, the wheat crop yield decreases in both the single- and double-cropping systems for both scenarios

(a) Nile basin



(b) Upper Blue Nile catchment

(c) Victoria catchment



(d) Nile delta catchment

Fig. 4 Mean crop yields in the Nile basin and selected local catchments for historical period (1971–2000) and projected period (2071–2100) under different cropping systems. Scenario A represents a setup without any cultivar adaptation and scenario B is a setup with adaptation to a late-maturing cultivar

(A and B) across the basin and catchments, however with a stronger decrease in the single-cropping system than the double-cropping system. We find the strongest yield declines in the Nile delta (Fig. 4d) where land use is dominated by wheat double cropping in this study. The crop yields in double-cropping systems of the Nile delta decrease by 52.1 ± 7.1% and 18.9 ± 6.6%, respectively in scenarios A and B. Considering that the Nile delta is predominantly irrigated, this shows that the growth stimulus from irrigation is likely to be overtaken by the negative impacts of rising temperatures on crop growth and yield.

Discussion

Comparison to other impact modelling studies

Although the mean rainfall is expected to increase in the Nile basin, average temperature is also projected to increase in the five GCMs used. Increasing mean temperatures in the region reduces the average length of the growing season by 14–40 days (Table 3) due to accelerated phenological development. A study by Ahmed (2021b) also shows that the Nile basin will experience shortened season lengths due to increasing trends of minimum and maximum temperatures. As a result, the regional crop yields are reduced both in the single- and double-cropping systems. However, the crop yield decrease signal is stronger in the single-cropping system than in the double-cropping system, most likely due to the fact that farmers with double-cropping systems will still harvest twice a year despite shortening of the growing seasons. Another likely scenario could include; the failure of the main cropping season due to climate factors can be compensated for in the second cropping season for farmers practicing double cropping. Hence, the double-cropping systems are more likely to be resilient against negative impacts of climate change than the single-cropping systems.

In comparison to other studies in Africa, Waha et al. (2013) implemented different cropping systems in SSA and the double-cropping systems had the least crop yield decrease in comparison to single-cropping systems even though different models, datasets and climate projections were used as in this study. In contrast to our results, Duku et al. (2018) reported that current sequential cropping areas will need to revert to single-cropping areas with future warming in the Upper Oume watershed in Central Benin. However, a comparison with these results is difficult as the study areas are in different climatic zones and crop phenology datasets and methodological approaches are different. Duku et al. (2018) also did not factor in CO_2 fertilization which has a significant effect on ET due to the decrease of stomatal conductance as atmospheric CO_2 increases, leading to a reduction of crop transpiration (Ficklin et al. 2009). Nevertheless, this shows that the methodology has a huge impact on model results.

The decrease in crop yields in the Victoria catchment and Nile delta have previously been reported by Bwambale and Mourad (2021) and Fawaz and Soliman (2016) respectively. However, in the Upper Blue Nile basin, the slight increase in projected mean crop yield is consistent with some studies such as Kassaye et al. (2021) and Ahmed (2021a) that reported a projected increase of some crop yields with future warming in Ethiopia and the Nile basin respectively. With respect to individual crops, Stuch et al. (2021) and Adhikari et al. (2015) projected a decline in crop yields of both maize and soybean respectively in East Africa by the end of the twenty-first century which is consistent with this study. Throughout the local catchments, wheat yields are consistently declining with climate change which has been reported as the most vulnerable crop by previous studies (Adhikari et al. 2015; Ahmed 2021a; Mostafa et al. 2021).

Cultivar adaptation

By adopting a late-maturing cultivar, coupled with an increase in CO_2 concentrations, the agronomic conditions for most crops (maize and soybeans) are projected to improve in most parts of the region keeping in mind that in areas where temperature increases may reach 6 to 7 °C, it is unlikely that the growing conditions of any crop will improve. In contrast, the same contention does not hold for wheat crops. These will still experience a decline in yields with future warming across the basin. This can be explained by the lower temperature optimum of wheat (Table 2), hence higher temperature stress at higher warming levels as compared to other crops that benefit from increased temperature. Various cultivar adaptations (early, medium and long maturing) have been investigated as an option for coping with changes in LGS due to future warming across the globe with several studies agreeing on the need to adapt late-maturing cultivars to counteract the effect of accelerated phenological development due to increased temperatures (Tao et al. 2016; Huang et al. 2020). However, crop-specific and site-specific results in this study suggest that adopting a late-maturing cultivar alone may not counter the effects of climate change for the wheat crop even though improvement in yield for maize and soybean is achieved. A study by Ali et al. (2020) for example showed how crop yield from two wheat cultivars, including a late-maturing cultivar decreased with climate change in the Nile delta. However, just like in our study, the reduction in crop yield of the late-maturing wheat cultivar was smaller under future warming.

Whereas late-maturing cultivars are found favourable in this study, access to these cultivars can be a constraint to the farmers in the basin, either due to lack of financial resources or lack of technology, e.g. genetic engineering to develop the cultivars. For example, some initiatives in SSA such as the Drought Tolerant Maize for Africa (DTMA) project has made different cultivar varieties including late-maturing varieties available to farmers in 13 African countries including some Nile basin countries (Kenya, Tanzania, Ethiopia and Uganda) (Fisher et al. 2015). However, the adoption of the new cultivars has largely been faced with barriers such as lack of resources, inadequate information, high seed price and farmer's perceptions of variety attributes (Fisher et al. 2015). In addition, small-holder farmers in Africa lack access to credit (Morris 2007), which impacts the adaptation potential. Hence, efforts to ensure access to credit, widespread awareness and understanding of the benefits of cultivar adaptation are continuously needed in the basin.

Of specific focus in this study is the impact on different cropping systems. Results show that the second cropping season of the adapted cultivar will also likely be successful under climate change translating into higher yields than a single-cropping system. Thus, farmers can profit from future warming through crop intensification by adopting a second cropping season. Although wheat is the only crop that consistently decreased in yield with future warming regardless of the cultivar simulated, the wheat double-cropping system was more resilient to climate change as the yield decline was smaller than in the single-cropping system. This suggests that farmers may lower the impact of climate change on wheat yields by adopting the double wheat cropping system in most parts of the region. In other climatic regions, Meza et al. (2008) demonstrated that double cropping is a more effective adaptation to cope with climate change in the Mediterranean regions compared to other management practices, e.g. use of early sowing dates. According to Ahmed (2021b), climate change will also impact sowing dates in the Nile basin. Yet, predicting the best sowing date remains a challenging task, especially in the tropics. Nevertheless, we cannot ignore the fact that increased double cropping could easily require additional resources such as energy, labour, nutrients, irrigation water and pesticides (Meza et al. 2008; VanWey et al. 2013; Waha et al. 2020a). Without incorporation of all these additional resources for double cropping in the modelling framework, the model might underestimate the feasibility of growing a second season, which could be a risk as the farmers will need to put all these resources into consideration. Additionally, adopting a double-cropping system might mean trading single-cropping seasons with a longer growing period for double-cropping seasons with slightly shorter growing periods. Therefore, the total biomass of the harvest crop in the main cropping season is reduced which has consequences for productivity and profits if grown for markets. Hence, there could still be substantial impacts of double-cropping systems in this study on crop production and household welfare at a local scale. However, with a double-cropping system, farmers are likely to have more crop security through crop-risk spreading and diversification to different crop cultivars or growing seasons.

Limitations of the modelling approach

There are several reasons that could explain the variance in simulated crop yield: (a) model structure, (b) model parameterization, (c) spatial resolution of input data, (d) biases in input data, (e) model calibration. Despite the low uncertainty ranges, a formal uncertainty analysis is recommended for future studies. Although overall the SWAT + model reflects the long-term average crop yield well, crop cycles are likely to have differences from year to year. Hence, further studies are recommended to focus on the interannual variability even though it was previously demonstrated that the model has difficulties in capturing annual variations (Epelde et al. 2015).

The multiple-cropping phenology dataset used in this study does not report planting and harvest dates of multiple years, so we assume no changes in the growing season or in the cropping systems between years in our simulations. However, farmers may adapt the cropping dates and cropping systems with climate change due to the variations in meteorological conditions. It is however unclear how fast and how often such adaptation in planting dates and cropping systems happens with a 30-year time period, but it can have a considerable positive or negative effect on crop yields that we could not consider. Also, the resolution of the phenology dataset (0.5°) may be too coarse to reflect local site-specific practices. For example, in this study, we only implemented double-cropping systems repeating the same crop as a compromise between accuracy and practicality since implementing other double-cropping systems on a detailed local scale would require more computational demand. This limits a detailed analysis of all double-cropping systems as farmers also implement different crops in different seasons (Waha et al. 2020a). For detailed local studies, site-specific observations should be used.

Other limitations in the modelling approach include the use of rather simplified simulation of the effects of increased atmospheric CO_2 concentrations and the use of only one emission scenario (SSP5-RCP8.5). In addition, precipitation projections over Africa are inconsistent amongst regional and global climate models with global models tending to project a wetter future compared to regional models (Dosio et al. 2021). Hence, the use of either regional or global climate projections could easily translate into different crop yields and adaptation implications. Another area of interest that was not covered in this study is the impact of extreme events on crop yields. Extreme weather events are expected to increase globally (Powell and Reinhard 2016); therefore, estimating their effects on crop yields is important for food security reasons. However, the results from this study provide an initial step towards estimation of how crop yields from different cropping systems in the Nile basin might be affected by future warming while more reliable databases and methodology can be developed and applied. Additionally, different responses of different cropping systems to climate change emphasize the need to include multiple-cropping systems in agricultural modelling studies for areas in which they occur, as simulating only single cropping could easily bias (under or overestimate) the yield results.

Conclusion

Future climate conditions with no cultivar adaptation will likely reduce crop yields for maize, soybean and wheat across different cropping systems in the Nile basin. The mean crop yield reduction is greater in single-cropping systems than in the double-cropping systems. Unlike the wheat crop yields, with an adaptation to a late-maturing cultivar, future warming impacts on crop yields of maize and soybean could be attenuated, with the mean crop yield increase greater in double-cropping systems than in the single-cropping systems. Thus, as different cropping systems respond differently to future warming, agricultural assessments should consider different cropping systems as an integral part of input data used by models to simulate crop yields and other indicators related to agricultural production. In addition, promoting late-maturing cultivars could help alleviate the likely impacts of climate change on some crops in the Nile basin. However, with double-cropping systems and late-maturing cultivars likely to be more resilient under climate change in the Nile basin, farmers should be aware of a trade-off between crop yields, production risks and resource availability. The insights gained from this study have important implications not only for the Nile basin crop production but also for the continental crop production to adapt to future climate change by adopting a climate-resilient cropping system. However, with the limitations related to the modelling process used such as, resolution of data, model parameterization and uncertainty analysis, future works are needed for a more extensive assessment of climate change impacts on cropping systems in the region especially for localized studies.

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Declarations

Competing interests The authors declare no competing interests.

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