Global cotton production under climate change - Implications for yield and water consumption

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Abstract. Being an extensively produced natural fiber on earth, cotton is of importance for economies. Although the plant is broadly adapted to varying environments, growth and irrigation water demand of cotton may be challenged by future climate change. To study the impacts of climate change on cotton productivity in different regions across the world and the irrigation water requirements related to it, we use the process-based, spatially detailed biosphere and hydrology model LPJmL. We find our modelled cotton yield levels in good agreement with reported values and simulated water consumption of cotton production similar to published estimates. Following the ISIMIP protocol, we employ an ensemble of five General Circulation Models under four Representative Concentration Pathways (RCPs) for the 2011–2099 period to simulate future cotton yields. We find that irrigated cotton production does not suffer from climate change if CO_2 effects are considered, whereas rainfed production is more sensitive to varying climate conditions. Considering the overall effect of a changing climate and CO_2 fertilization, cotton production on current cropland steadily increases for most of the RCPs. Starting from ~65 million tonnes in 2010, cotton production for RCP4.5 and RCP6.0 equates to 83 and 92 million tonnes at the end of the century, respectively. Under RCP8.5, simulated global cotton production raises by more than 50% by 2099. Taking only climate change into account, projected cotton production considerably shrinks in most scenarios, by up to one-third or 43 million tonnes under RCP8.5. The simulation of future virtual water content (VWC) of cotton grown under elevated CO_2 results for all scenarios in less VWC compared to ambient CO_2 conditions. Under RCP6.0 and RCP8.5, VWC is notably decreased by more than 2,000 m^3t^{-1} in areas where cotton is produced under purely rainfed conditions. By 2040, the average global VWC for cotton declines in all scenarios from currently 3,300 to 3,000 m^3t^{-1} and reduction continues by up to 30% in 2100 under RCP8.5. While the VWC decreases by the CO_2 effect, elevated temperature acts in the opposite direction. Ignoring beneficial CO_2 effects, global VWC of cotton would increase for all RCPs except RCP2.6, reaching more than 5,000 m^3t^{-1} by end of the simulation period under RCP8.5. Given the economic relevance of cotton production, climate change poses an additional stress and deserves special attention. Changes in VWC and water demands for cotton production are of special importance, as cotton production is known for its intense water consumption. The implications of climate impacts on cotton production on the one hand, and the impact of cotton production on water resources on the other hand illustrate the need to assess how future climate change may affect cotton production and its resource requirements. Our results should be regarded as optimistic, because of high uncertainty with

respect to CO_2 fertilization and the lack of implementing processes of boll abscission under heat stress. Still, the inclusion of cotton in LPJmL allows for various large-scale studies to assess impacts of climate change on hydrological factors and the implications for agricultural production and carbon sequestration.

1 Introduction

Being an extensively produced natural fiber on earth, cotton (*Gossypium Spp*) is providing income to millions of farmers. According to the World Bank Atlas (Sheth, 2017), eight of the top-10 cotton-producing countries are classified as developing countries and their exports of the crop reached $\sim$ US\$ 30 billion in 2017 (ITC, 2019) (full overview in Table S1). Particularly in the West African region – the world's third largest cotton exporter (following North America and Central Asia) – cotton has played an important part in the economic development and has remained a key source of livelihood for many farmers (Hussein et al., 2005; Perret and Bossard, 2006). Worldwide, cotton is already broadly adapted to growing in temperate, subtropical and tropical environments, but growth may be challenged by future climate change (Bange et al., 2016). Climate change is likely to affect cotton production both positive and negative. Temperature influences cotton growth and development by determining rates of fruit production, photosynthesis and respiration (Turner et al., 1986; Hearn and Constable, 1984).

However, the growth of cotton plants differs at varying stages of plant development and by plant organ (Burke and Wanjura, 2010) and thus a temperature optimum for cotton cannot be defined. Yield and growth of cotton are directly affected by a high temperature. Additionally, hot weather conditions increase the evaporative demand in cotton plants leading to more intense water stress (Hall, 2000). Elevated atmospheric carbon dioxide concentrations ($[CO_2]$) on the other hand are expected to increase cotton yields as cotton is a C_3 crop (Kimball, 2016). Numerous FACE studies demonstrated a strong reaction of cotton yield and growth to an increased CO_2 concentration (Kimball, 1983; Cure and Acock, 1986; Hileman et al., 1994; Hendrix et al., 1994; Reddy et al., 1997; Mauney et al., 1994; Bhattacharya et al., 1994). Likewise, water-use efficiency (WUE) can be improved by CO_2 enrichment because it increases biomass and causes partial stomatal closure at the same time, consequently reducing transpiration (Mauney et al., 1994; Hileman et al., 1994; Broughton, 2015; Ko and Piccinni, 2009).

Crop models have been used to assess the effect of changing climate conditions on crop productivity but the main focus has been on major staple crops, such as maize, wheat, rice and soybean (e.g. Challinor et al., 2014; Rosenzweig et al., 2014; Müller et al., 2015; Pugh et al., 2016; Schleussner et al., 2018) that provide the majority of calories to human nutrition (Yahia et al., 2019; Welch and Graham, 2004).

The response of other crops has been assessed less thoroughly, despite their importance for economies or human nutrition. With this study, we aim to examine the impacts of climate change on cotton productivity in different regions across the world. We therefore add cotton as an additional crop to the global dynamic vegetation, hydrology and crop growth model LPJmL version 4.0 (Schaphoff et al., 2018b). We provide an evaluation of model skill by comparing simulated cotton yields to yield statistics (FAO et al., 2018). To study climate change impacts on future cotton productivity, we simulate future cotton yields and related irrigation water requirements under a set of future climate scenarios (Hempel et al., 2013), following the ISIMIP protocol (Warszawski et al., 2014).

2 Materials and Methods

2.1 The LPJmL model

The global dynamic vegetation model LPJmL is a well-established and thoroughly evaluated model (Schaphoff et al., 2018b, a; Müller et al., 2017) that is unique in combining natural vegetation, hydrology and managed ecosystems (croplands, pastures) in one consistent framework for gridded large-scale applications. The model has been extensively described by Schaphoff et al. (2018b) and we here only provide a short summary of the most relevant features for this study and the extensions implemented for cotton. Agricultural crops have been implemented as annual crops with daily computation of photosynthesis, autotrophic respiration, evapotranspiration and allocation of assimilates to plant organs (Bondeau et al., 2007). Individual crops are grown on separate spatial units (stands) within each grid cell so that different crops do not compete for water and light, mimicking monocultures. Also purely rainfed and irrigated crop cultivation can be simulated on separate stands and irrigation water can be applied by different irrigation techniques and can be limited by actual freshwater availability (Jägermeyr et al., 2015). LPJmL – here operated at a 0.5 arc-degree (°) spatial resolution – simulates processes underlying the growth and productivity of both natural and agricultural vegetation (Sitch et al., 2003; Bondeau et al., 2007; Lapola et al., 2010; Rolinski et al., 2017). The model represents 10 plant functional types (PFT) as well as 12 crop functional types (CFT) and three bioenergy plantation systems (Beringer et al., 2011). In LPJmL, carbon, water and energy fluxes are closely linked to reproduce plant growth dynamics and to account for the effects of changes in climate conditions and water availability (Gerten et al., 2004, 2007). Several features such as river routing (Rost et al., 2008a), irrigation systems (Jägermeyr et al., 2015), a soil hydrological and carbon distribution scheme (Schaphoff et al., 2013), and a fire module (Thonicke et al., 2010) further improved the model. The calculation of photosynthesis is based on the Farquhar model (Collatz et al., 1991; Haxeltine and Prentice, 1996; Sitch et al., 2003). Water consumption is ruled by plant physiology and the coupling between vegetation and water cycle enables the separation of productive (transpiration) and unproductive (interception, evaporation) portions of plant water use. Moreover, water flows are divided into green (precipitation) and blue (irrigation) water (Rost et al., 2008b; Jägermeyr et al., 2015, 2016). The evaluation of various model components, e.g. crop yields, evapotranspiration and river discharge has shown that LPJmL is a tool suitable to analyse changes in vegetation and water. Schaphoff et al. (2018a) provide a comprehensive evaluation of the LPJmL model.

2.2 Implementation and parameterization of cotton

Twelve crop types are already implemented in LPJmL (temperate and tropical cereals, pulses, maize, rice, temperate and tropical roots, sunflower, soybeans, groundnut, rapeseed, sugar cane) (Bondeau et al., 2007; Lapola et al., 2010). In this study we include cotton, which was originally implemented as a perennial crop in LPJmL by Fader et al. (2015) for the Mediterranean region. However, in most parts of the world, cotton is cultivated as an annual crop (Ritchie et al., 2007; Whitaker et al., 2018). We modify the modeling approach developed by Fader et al. (2015) accordingly and implement cotton into LPJmL version 4.0 (Schaphoff et al., 2018b) as an annual crop. Similar to Fader et al. (2015), the cotton plant is simulated and parameterized as an agricultural tree and we calculate phenology and growth on a daily basis (see below). We adopt most of the key parameters

used by Fader et al. (2015) and adjust values for plant density and temperature optimum for photosynthesis (Table 1). Other than adjusting these two parameters, we did not calibrate any plant growth parameters. To account for regional differences, we use country-specific planting densities provided by several studies (Section 2.2.2). As the intensitiy of irrigation on irrigated

95   cotton producing areas in the different production regions is unknown, we conduct simulations with different levels of deficit irrigation (25, 50, 75, and 100% of required irrigation water) and select the irrigation level that produces the cotton yield that is closest to observations (Section 2.3). In this study, simulated cotton yields should be understood as the entire cotton fruit, that is both cotton lint and cottonseed.

Table 1. Key parameters of cotton according to Fader et al. (2015). Values marked with an asterisk (*) were adjusted. $\mathbf{K_{est}}$: tree density range; **HR**: harvest ratio; $\mathbf{T_b}$: base temperature; $\mathbf{Ph_{opt}}$: optimum temperature range for photosynthesis; $\mathbf{T_{lim}}$: lower and upper coldest monthly mean temperature; **WCF**: conversion factor (moisture content) from dry to fresh matter.

Crop	Seasonality	K_{est} (trees ha^{-1})	HR (frac)	T_b ($^\circ$C)	Ph_{opt} ($^\circ$C)	T_{lim} ($^\circ$C)	WCF (% of DM)
Cotton	Deciduous broadleaved	30,000 - 100,000*	0.19	15	16 to 32*	-10 to 40	91

2.2.1 Phenology and growth

100   Wild cotton is a deciduous perennial tree and the fruiting habit of the plant is not clearly established, i.e. vegetative and reproductive growth occur at the same time (Ritchie et al., 2007). During the growing period the leaves supply photosynthates to plant growth and the developing fruit and are shed only when the plant is stressed such as during drought, disease, nutrient starvation or frost (Wullschleger and Oosterhuis, 1990). The perennial nature of cotton, even its modern cultivars, is not helpful in achieving high yields of cotton lint and seed. Consequently, through breeding and changes in cultivation practices, cotton is

105   now farmed as an annual crop to prevent diseases and optimize cotton production (Ritchie et al., 2007; Whitaker et al., 2018). Once the entire crop is mature, the leaves serve no useful purpose and their removal can be beneficial for mechanical harvesting. Crop maturity is characterized by slowed development of new main-stem nodes, causing first-position white flowers to appear progressively closer to the plant apex (Oosterhuis et al., 1992). The development of cotton plants is particularly sensitive to temperature leading to an acceleration of all stages of phenological development (Bange et al., 2001; Hodges et al., 1993;

110   Reddy et al., 1997). However, being an indeterminate plant, the phenological phases of cotton cannot be clearly distinguished and represented as a function of temperature (Bange et al., 2016) and the growing period is thus not necessarily shortened by warming as e.g. observed in annual crops.

To account for the current production system, cotton is implemented in LPJmL as small agricultural trees that are planted annually and removed at the end of the growing period, representing the annual production mode.

115   The phenology, i. e. the temporal dynamic of the canopy greenness is computed with the growing season index (GSI) concept as described and parameterized by Forkel et al. (2014). The daily phenology status is determined by multiplying limiting effects of cold temperature, short-wave radiation, water availability, and heat stress. Thus, vegetation greenness is limited by temperature-induced heat stress. The saplings are initialized with 2.3 gC of sapwood and a leaf-area index (LAI) of 1.6 m^2 m^{-2}.

Similar to phenology, gross primary production (*GPP*) and net assimilation (*NPP*) of cotton plants are calculated daily. Increasing daily air temperature values lead to a higher respiration (maintenance) rate which can exceed carbon assimilation, resulting in a negative NPP (Schaphoff et al., 2018b). Fruit growth is expressed as daily carbon accumulation (C_{fruit}) of a fraction of *NPP* after square set, i.e. as soon as squares (pre-bloom fruiting buds) emerge. Square form at the initiation of a fruiting branch. The model implementation assumes that cotton fruit growth occurs after the fractional cover of green leaves has reached 60 % of full leaf cover, i.e. the phenology scaler *phen*=0.6. This follows the description of Ritchie et al. (2007) on the canopy and fruit development of cotton plants.

$$C_{fruit} = max(0, NPP)xHR \tag{1}$$

where *HR* is the harvest ratio and *NPP* the daily net primary productivity of the tree. On days with negative *NPP*, fruit growth is halted but accumulated yield is not reduced, reflecting that boll development dominates plant growth at this stage of reproductive growth (Ritchie et al., 2007). At the end of the growing period, cotton harvest *H* is determined as

$$H = \sum_{D_S}^{D_H} C_{fruit} \tag{2}$$

where the day of square set (D_S) and harvest day (D_H) define the length of the simulated reproductive period.

A possible simultaneous establishment of herbaceous PFTs in the same areas of agricultural trees, representing grasses and weeds (for modelling details see Schaphoff et al. (2018b)), can be simulated by LPJmL, but was turned off in the simulations here. This mimics effective weed control, mainly practiced in cotton farming today to reduce competition for water and nutrients (Ritchie et al., 2007; Whitaker et al., 2018).

2.2.2 Specification of planting densities, sowing dates and irrigation

A country-specific planting density (k_{est}) is used as model input, which is, apart from irrigation and sowing dates, the only management aspect that is explicitly considered. These country-specific planting densities have been taken from literature (Abdullaev et al., 2007; Iqbal et al., 2012; Venugopalan et al., 2013; Dong et al., 2006; Bednarz et al., 2006; Zhi et al., 2016; Khan et al., 2017; Bozbek et al., 2006; Echer and Rosolem, 2015; Dai and Dong, 2014; Vaughan, 2005; Akhtar et al., 2002) and are shown in Figure S1. The cotton specific planting density parameter (plants $m^{-2} a^{-1}$) was introduced similar to the annual establishment rate k_{est} of PFT individuals (Schaphoff et al., 2018b).

The growing season of cotton plants is prescribed from the sources specified in section *Modeling protocol, input and reference data*. Thereby the sowing date defines the start of the growing period and ranges between Julian day 1 and 335 of the year of sowing. The prescribed growing season length varies from 153 to 243 days of year for cotton plants to reach harvest.

Five hydrologically and thermally active layers represent the soil profile in LPJmL where roots access water, depending on their PFT/CFT-specific root distribution (Schaphoff et al., 2018b). The soil water content of the first layer determines the

infiltration rate and water not infiltrated forms the surface runoff. Similar to the infitration approach, the percolation rate is limited by soil moisture of the lower layer and excess water above saturation feeds the lateral runoff (Schaphoff et al., 2013).

150   Cotton is produced in rainfed or irrigated systems, whereat irrigation generally serves to reduce the impacts of rainfall deficits and thus reduces interannual yield variability. However, the actual amount of water applied to fields is unknown and determined by water availability, water management systems and economic rationale. The extent to which rainfall deficits are compensated by irrigation is thus not only a question of equipment for irrigation (Portmann et al., 2010) and water stress can still affect interannual yield variability in irrigated systems. In order to test the importance of deficit irrigation for cotton

155   production, we performed several runs varying the fraction of soil pore space filled up in individual irrigation events from 0 (corresponding to purely rainfed conditions) to 1 (meets full irrigation demand) by increments of 0.25.

If the soil water content in the upper 50 cm of the soil falls below 90% of field capacity an irrigation event is triggered. Soil water lower than atmospheric water demand requires a daily net irrigation (NIR; mm). NIR is calculated as the amount of water needed to fill soil water up to field capacity W_{fc} in that upper root layers of the soil.

160     $$NIR = max(0, (W_{fc} - w_a)) \tag{3}$$

where w_a is the soil water in millimeters actual available .

Inefficiencies of different irrigation systems cause additional water needs to meet crop water demand. For that reason, LPJmL considers conveyance efficiency and calculates application requirements (*AR*) for each system. Consequently, the gross irrigation requirement (*GIR*; mm), i.e. the amount of water requested for abstraction results in

165     $$GIR = \frac{NIR + AR - Store}{E_c} \tag{4}$$

where *Store* is a storage buffer. The storage buffer is filled up with available irrigation water not used due to available precipitation and is released in the next irrigation event. A detailed explanation about the computation of *NIR*, *GIR*, and *Store* in LPJmL is given in Rost et al. (2008b) and Jägermeyr et al. (2015). The application requirements *AR* are calculated as

$$AR = max(0, (W_{sat} - W_{fc})xDU - w_{fw} \tag{5}$$

170   where W_{sat} is the soil moisture content at saturation level (in mm); *DU* is an irrigation system-specific scalar (no unit), to distribute irrigation water uniformly across the field, and w_{fw} is the available free water (in mm) (Jägermeyr et al., 2015). Note that the computation of *GIR* is relevant for simulations, in which irrigation water is constrained by available river discharge and reservoir capacity (e.g. Jägermeyr et al., 2015), but not here, where we assume explicit levels of deficit irrigation but no additional constraints on water limitation.

175   This model development is based on LPJmL4, a model version that does not account for nutrient limitations and, thus, fertilizer effects are not considered.

2.3 Modeling protocol, input and reference data

All simulations are conducted at a spatial grid of 0.5° longitude/latitude resolution with daily weather input data and annual data on atmospheric carbon dioxide concentrations ($[CO_2]$). To simulate historical results, we ran the LPJmL model for the period 1901 – 2011 using the Climate Research Unit's (CRU) TS 3.23 monthly data for temperature, wet days and cloudiness (Harris et al., 2014), and precipitation data (Version 5) provided by the Global Precipitation Climatology Centre (GPCC) (Rudolf et al., 2011). Monthly weather input data is converted to daily data, using an internal weather generator (Schaphoff et al., 2018b). Data on $[CO_2]$ refers to records at the Mauna Loa station (Tans and Keeling, 2015). A 120-year spin-up (recycling the first 30 years of input climatology) preceded transient runs to bring water fluxes and soil temperatures into dynamic equilibria. As soil carbon pools have no effect on cotton productivity in this version of the model, a longer spinup to correctly initialize soil and vegetation carbon pools (Schaphoff et al., 2018b) is not necessary here. Simulations for future periods are conducted for four different Representative Concentration Pathways (RCPs), RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (Moss et al., 2010), each implemented by five different General Circulation Models (GCMs): GFDL-ESM2M (Dunne et al., 2012, 2013), HadGEM2-ES (Jones et al., 2011), IPSLCM5A-LR (Dufresne et al., 2013), MIROC-ESM (Watanabe et al., 2011), and NorESM1-M (Bentsen et al., 2013) that have been bias-corrected as described by Hempel et al. (2013). Data on $[CO_2]$ for future periods is taken from the corresponding RCP data sets (Moss et al., 2010) as provided by the ISIMIP project (Frieler et al., 2017). To assess how cotton plants respond to future climate change we ran the model for the time span 1951 – 2099, again preceded by a 120-year spin-up period. The averaging time for historical yields differs (depending on the purpose) and is indicated for each figure. Future yield projections are presented as 2070 – 2099 averages, compared to annual means averaged over the reference period 1980 – 2009, or as full time series. The spatial distribution of cropland dedicated to cotton was taken from the land-use data set MIRCA2000 (Portmann et al., 2010) which provides both rainfed and irrigated harvested areas around the year 2000 with a spacial resolution of 5 arc min (Figure S2).

Sowing dates and growing period were provided as gridded model input, combining sowing and harvest information provided by the ICACs World Cotton Calendar (WCC) (Committee, 2014) and Portmann et al. (2010). More precisely, we used the WCC data and filled gaps with data offered by MRICA (Figure S3). Because increasing temperatures do not necessarily shorten the period of growth for cotton plants (Bange et al., 2010; Luo et al., 2014a) and parameterization of cotton partly reflects more advanced cultivars (Section 2.2), we here assume that the growing season length remains static in all simulations.

Cotton yield levels modeled under different irrigation options on irrigated cotton areas (Section 2.2.2) were compared with national yield levels published by FAO et al. (2018), reported as "Seed cotton" there. Since LPJmL is a global model, we evaluated the model at global and national level. However, on grid cell level simulated cotton yield results were also tested against semi-controlled field experiments. For these comparisons management assumptions (sowing and harvest dates, planting densities) were adapted to reproduce experimental conditions (Figure S8).

3 Results

3.1 Evaluation of model performance

In order to evaluate the performance of this extended LPJmL model version, simulated historical cotton yields are compared to observed data (Figure 1) published by FAOstat (FAO et al., 2018). The modelled cotton yield levels are in good agreement with reported values. Statistical analyses for both, the top-10 cotton-producing countries and for cotton-growing countries in West Africa show that simulated national yield levels can well reproduce reported national yield levels (Figure 1). For the top-10 cotton-producing countries, cotton yields simulated under full irrigation often match FAO values best. The whiskers that depict the range of yield levels simulated with different irrigation options on the irrigated cotton cropland often reach the zero line, indicating that cotton production in these countries (Pakistan, Turkmenistan, Turkey, Uzbekistan etc.) is not possible without irrigation. National yield levels can also be reproduced well in West Africa, where in contrast to the top-10 producer countries hardly any irrigated cotton production exists (Figure S2). An overview of the model performance for all cotton-growing countries is given in the supplementary information, Table S2.

For these simulations, the planting densities in LPJmL have not been calibrated against observed yield levels, but are based on reported planting densities (Figure S1).The model simulations can reproduce statistically significant shares of reported variability in time of intensely-managed top-producing countries, such as the USA and Australia as well as a few West African countries (Figures 2 and S4) and other countries (Table S2).The model also reproduces some of the historical interannual variation in global cotton production (Figure 3). The spatial pattern of cotton yields is shown in Figure S5.

We further evaluate the model results with respect to the water consumption of cotton production against data provided by (Chapagain et al., 2006), averaged over the time period 1997-2001. For reasons of comparability, we therefore followed the concept of "virtual water content" (Allan, 1997, 1998) and calculated the virtual water content of cotton ($t\,m^{-3}$) as the ratio of the water (green and blue in $m^3\,ha^{-1}$) used to grow a crop in the field to the related crop yield ($t\,ha^{-1}$). We find that LPJmL simulations of water consumption of cotton production are in good agreement with the estimates of (Chapagain et al., 2006) with respect to the order of magnitude and spatial variability (Figure S6 and Table 2). The virtual water content is quite variable across regions and mainly in an inverse relation of the yield pattern (Figure S5), suggesting that spatial yield variability is higher than the spatial variability in actual evapotranspiration (AET). As virtual water content is a criterion for water-use efficiency (Hoekstra, 2003; Hoekstra and Mekonnen, 2012; Zhuo and Hoekstra, 2017), moderate values in regions with high irrigation shares (compare Figures S6 and S7) point to an efficient use of (blue) water. The efficiency of blue-water use depends on management practices, such as irrigation techniques, irrigation strategies, and mulching practices (Gleick, 2003; Perry, 2007; Perry et al., 2009; Zhuo and Hoekstra, 2017) to reduce non-beneficial losses (soil evaporation) as well as on other yield-reducing factors, such as nutrient limitations or pests. In the Indo-Gangetic plain, drip irrigation of cotton is only applied in experimental fields and farmers grow cotton by applying irrigation water through flood irrigation (Thind et al., 2008; Aujla et al., 2008). Here, the water consumption of cotton production is at the high end, indicating substantial non-beneficial water losses (Thind et al., 2010).
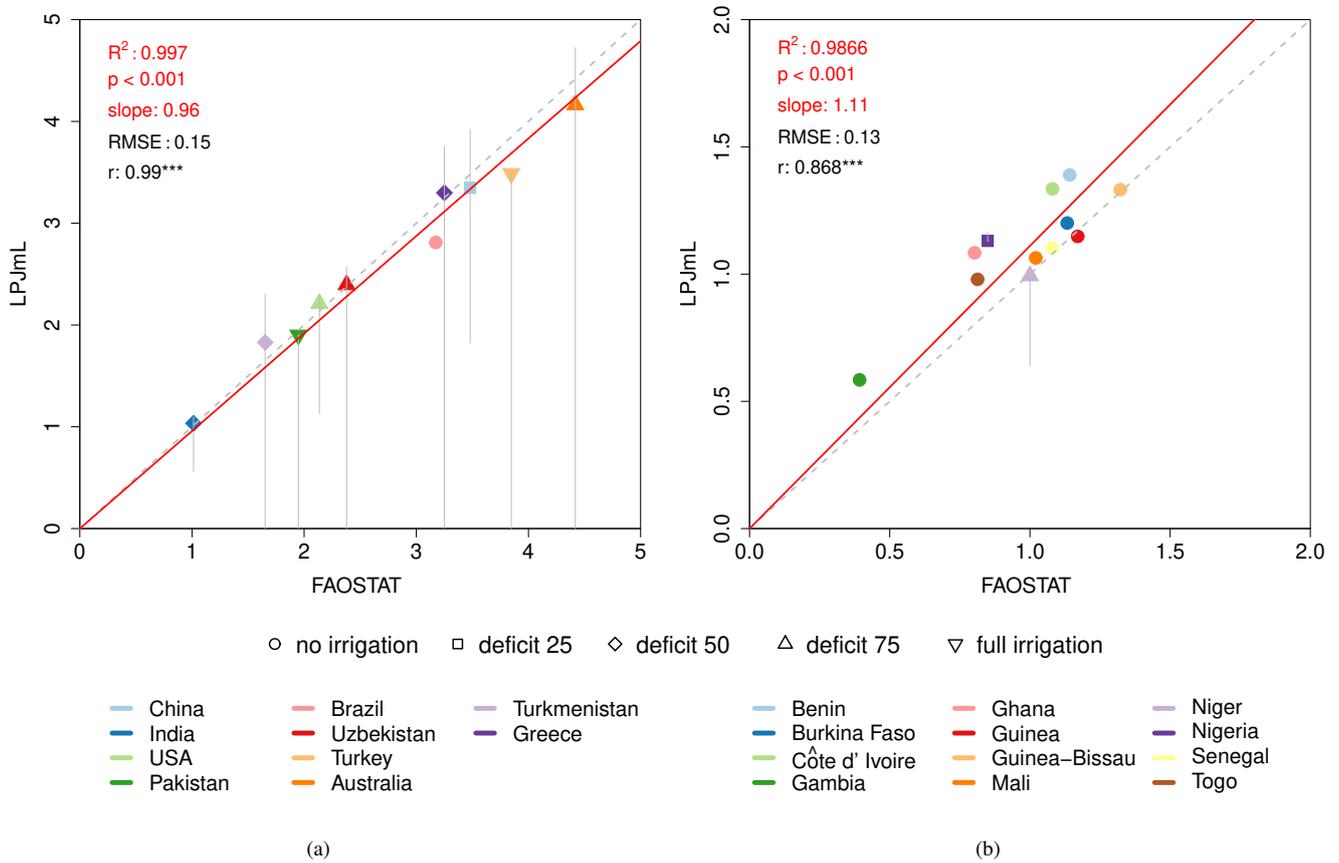
Figure 1. Comparing simulated cotton yields [t ha^{-1}] to observed values for (a) the top-10 cotton producing countries and (b) West African countries. Whiskers indicate the yield range of different irrigation options on irrigated cotton cropland in these countries (Portmann et al., 2010). LPJmL yield data and FAOSTAT yield data were both averaged over the time period 2000-2009.
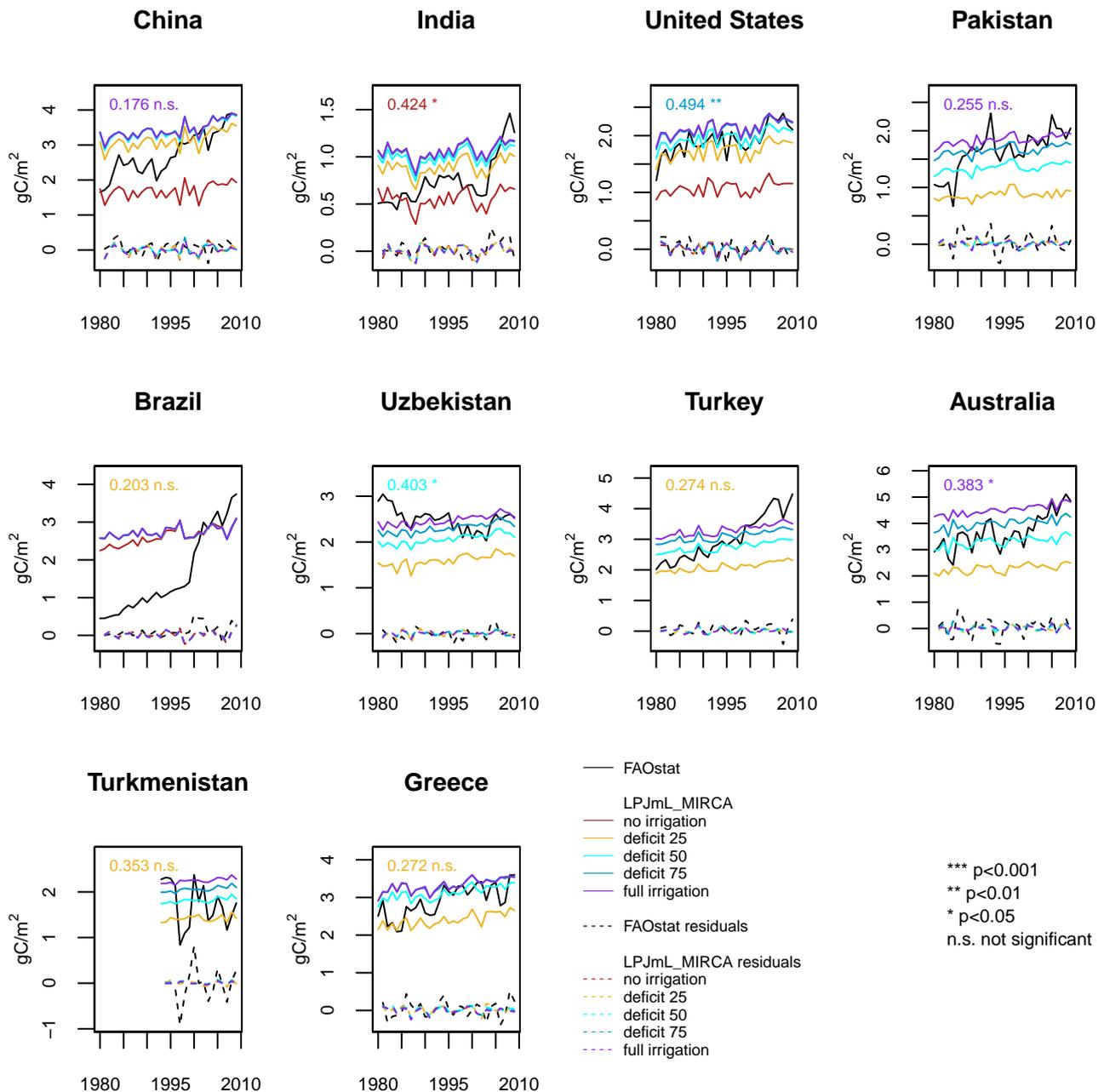
Figure 2. Comparing interannual yield variability for the top-10 cotton producing countries. Numbers in each plot depict the correlation coefficient between simulated residuals and FAOSTAT residual data. The different irrigation options (on irrigated cropland only) are shown in coloured lines. The colour of the correlation coefficient indicates to best fitting irrigation option. For Turkmenistan, yields have only been reported from 1992 onward (FAO et al., 2018), so only these years are shown in the plot.
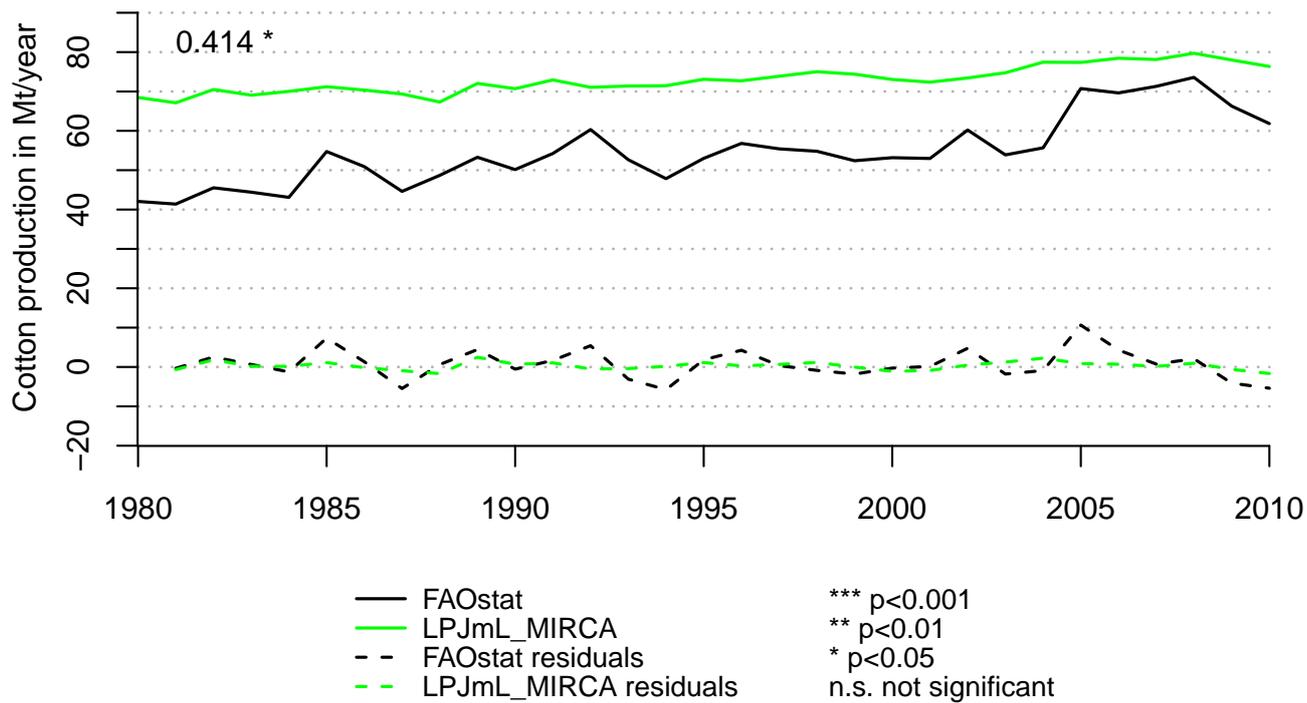
Figure 3. Time series of historical global cotton production [million tonnes/year]. The number in the plot depicts the correlation coefficient between simulated residuals and FAOSTAT residuals.

Table 2. Virtual water content and consumptive water use for cotton production in the major cotton producing countries for the period 1997-2001. Reference data taken from Chapagain et al. (2006), here referred to as *"C06"*. VWC_{blue}: blue virtual water content, VWC_{total}: total virtual water content, A_{irrig}: irrigated harvested cotton area, A_{total}: total harvested cotton area.

| | Virtual water content [m^3/ton] | | | | VWC_{blue}/VWC_{total} | | A_{irrig}/A_{total} | | Consumptive water use [mm] | | | |
| | Total | | Blue | | | | | | Total | | Blue | |
	LPJmL	C06	LPJmL	C06	LPJmL	C06	LPJmL	C06	LPJmL	C06	LPJmL	C06
Argentina	2,564	7,700	142	2,307	0.06	0.30	0.08	1	775	877	43	263
Australia	2,536	2,278	1,677	1,408	0.66	0.62	1	0.9	1,177	843	778	521
Brazil	3,235	2,621	20	46	0.01	0.02	0.02	0.15	895	551	5	10
China	1,907	2,018	481	760	0.25	0.38	0.41	0.75	716	638	180	240
Egypt	2,727	4,231	2,605	4,231	0.96	1.00	1	1	963	1,009	921	1,009
Greece	2,554	2,338	1,586	1,808	0.62	0.77	1	1	937	707	582	547
India	5,232	8,662	1,773	2,150	0.34	0.25	0.36	0.33	563	538	191	134
Mali	5,738	5,218	0	1,468	0.00	0.28	0	0.25	594	538	0	151
Mexico	4,191	2,508	2,538	1,655	0.61	0.66	0.97	0.95	933	746	565	492
Pakistan	5,486	4,914	4,377	3,860	0.80	0.79	1	1	1,033	850	824	668
Syria	2,689	3,339	2,005	3,252	0.75	0.97	1	1	1,008	1,309	751	1,275
Turkey	2,779	3,100	1,796	2,812	0.65	0.91	1	1	943	963	609	874
Turkmenistan	4,076	6,010	3,538	5,602	0.87	0.93	0.98	1	926	1,025	804	956
USA	3,461	2,249	966	576	0.28	0.26	0.37	0.52	775	419	216	107
Uzbekistan	3,616	4,460	2,854	4,377	0.79	0.98	1	1	911	999	719	981
Global average	3,338	3,644	1,397	1,818	0.42	0.50	0.491	–	755	–	320	–

For the evaluation of the modeled cotton yield response to elevated [CO$_2$], we compare simulated yield effects to those reported from Open-Top Chamber (OTC) and Free Air Carbon dioxide Enrichment (FACE) experiments. Kimball (2016) report strong yield increases in cotton bolls under elevated [CO$_2$] (~38 %), which is a stronger yield response than most other crops. Experimental data from Kimball et al. (1992) and Mauney et al. (1994) also show that the level of water and nutrient availability affects the relative cotton yield response to elevated [CO$_2$]. Similarly, LPJmL yields also result in a strong response depending on the level of [CO$_2$] increase and water stress (see Figure S8). Observational data are only available for one OTC site (Phoenix, AZ, USA) and one FACE site (Maricopa, AZ, USA) so that it remains unclear how the cotton yield response to

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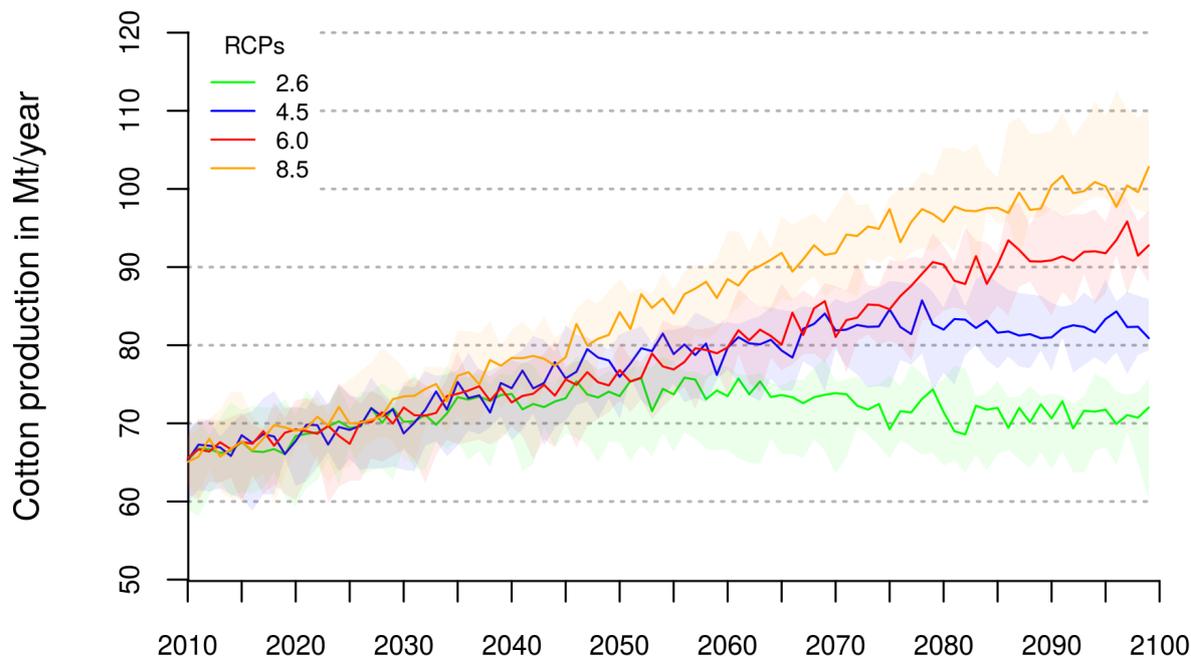
Figure 4. Simulated global cotton production [million tonnes] for different RCPs. Transparent colours show the uncertainty ranges of 5 different GCM patterns.

elevated [CO_2] varies across different climate zones and management regimes. However, the range of simulated yield increases under elevated [CO_2] seems to be often adequately reproduced by LPJmL in the corresponding grid cells (Figure S8).

3.2 Climate change impacts on cotton production

Considering the overall effect of climate change and CO_2 fertilization, future cotton productivity slightly increases – starting from ~65 million tonnes in 2010 – until 2040 for all RCPs similarly by ~10 %. For RCP2.6, global cotton production on current cropland slightly declines after 2040, while for the remaining RCPs simulated production on current cropland steadily increases. Looking at RCP4.5 and RCP6.0, cotton production equates to 83 and 92 million tonnes at the end of the century, respectively. Under RCP8.5, simulated global cotton production raises by more than 50 % up to 102 million tonnes by 2099 (Figure 4 and Figure S9 for relative changes).

Spatial patterns of projected changes in cotton yields (Figure S10) show that increases are mainly expected in cooler or irrigated environments (Figure S2), but exceptions exist, such as Pakistan and northern India, where cotton yields are projected to only slightly increase despite irrigation. Overall, the spatial patterns of projected yield increases seem to be quite static but scale with the emission scenario (RCP; Figure S10).

The projected increases in yield are the result of interacting processes, which are often dominated by a positive response to elevated [CO_2]. Higher temperatures initially stimulate cotton plant growth by accelerating phenological processes and

thus reaching full canopy closure earlier in the season. If, however, high temperatures persist throughout the growing season,
265 phases of plant stress (heat and water stress) emerge earlier and then reduce leaf cover and halt the reproductive growth of
cotton plants. This yield-decreasing effect of climate change is masked by the strong growth-stimulating effect of elevated
$[CO_2]$ (see figures S11 and S12 for simulations with static $[CO_2]$, where yields continuously decline with increasing climate
change).

Without the beneficial effect of elevated $[CO_2]$, climate change leads to yield declines in most of the current cotton pro-
270 duction area (Figure S13). Across all RCPs the spatial variation of impacts shows a diverse pattern, resulting in climate-only
induced yield losses up to $2 \, \text{t ha}^{-1}$ in large parts of the cotton production area. Projected cotton yields for the high-end emission
scenario (RCP8.5) decline significantly in Bolivia, Argentina, Iraq, Syria, and Egypt. Considerable losses are also projected for
the USA, Brazil, India, Pakistan, Central Asia, the southeastern part of China, and Australia if no effects of CO_2 fertilization
are assumed. Only for Peru, Northeast-China and some parts of Central Asia, the simulations project sustained cotton yield
275 gains under climate change only.

3.3 Climate change impacts on irrigation water consumption

While changes in atmospheric CO_2 may turn into enhanced water use or water-use efficiency of cotton production, the impact
of elevated CO_2 on cotton growth depends also on plant water availability. The simulation of future virtual water content of
cotton grown under elevated CO_2 results for all scenarios in less virtual water content compared to ambient CO_2 conditions
280 (Figure 5). While there is only a slight decrease in virtual water content of cotton under RCP2.6, this effect is continuously
strengthened across the emission scenarios (RCPs) for both well-watered and water-stressed conditions. Under RCP6.0 and
RCP8.5, virtual water content is notably decreased by more than $2,000 \, \text{m}^3\text{t}^{-1}$ in areas where cotton is produced under purely
rainfed conditions, e.g. in West Africa and India. By 2040, the average global virtual water content for cotton declines in
all scenarios from currently 3,300 to $3,000 \, \text{m}^3\text{t}^{-1}$ (Figure S14(a)). Thereafter it slightly increases again under RCP2.6 while
285 reduction continues for the remaining scenarios until end of the century. The most considerable decrease by 30% results in
2100 under RCP8.5 (Figure S14(b)). The projected reduction of VWC of cotton is predominantly caused by increased cotton
productivity, not by a reduction in cotton water consumption, i.e. the amount of water evapotranspired in cotton fields. Global
cotton water consumption slightly increases from currently ~$235 \, \text{km}^3$ by 3.6% and 3% at the end of the century under RCP2.6
and RCP8.5, respectively.
290 While the virtual water content improves by the CO_2 effect, elevated temperature (and water stress) act in the opposite
direction. Except for the RCP2.6, the global virtual water content of cotton increases slightly but steadily under RCPs until
mid century. For RCP4.5 and RCP6.0 this development continues resulting in a virtual water content roughly 10% above the
current value by 2100 (Figure S15(b)) if no CO_2 effect is assumed. The most obvious alteration is projected for RCP8.5 where
the changing climate without accounting for the CO_2 effect leads to an average global virtual water content of more than
295 $5,000 \, \text{m}^3\text{t}^{-1}$ by end of the simulation period (Figure S15(a)). The spatial pattern reveals that in all scenarios the virtual water
content increases in all regions if CO_2 effects are not accounted for. However, most drastic changes occur again in West Africa
and India, where also the strongest changes are observed when CO_2 effects are accounted for. While the CO_2 effect leads to
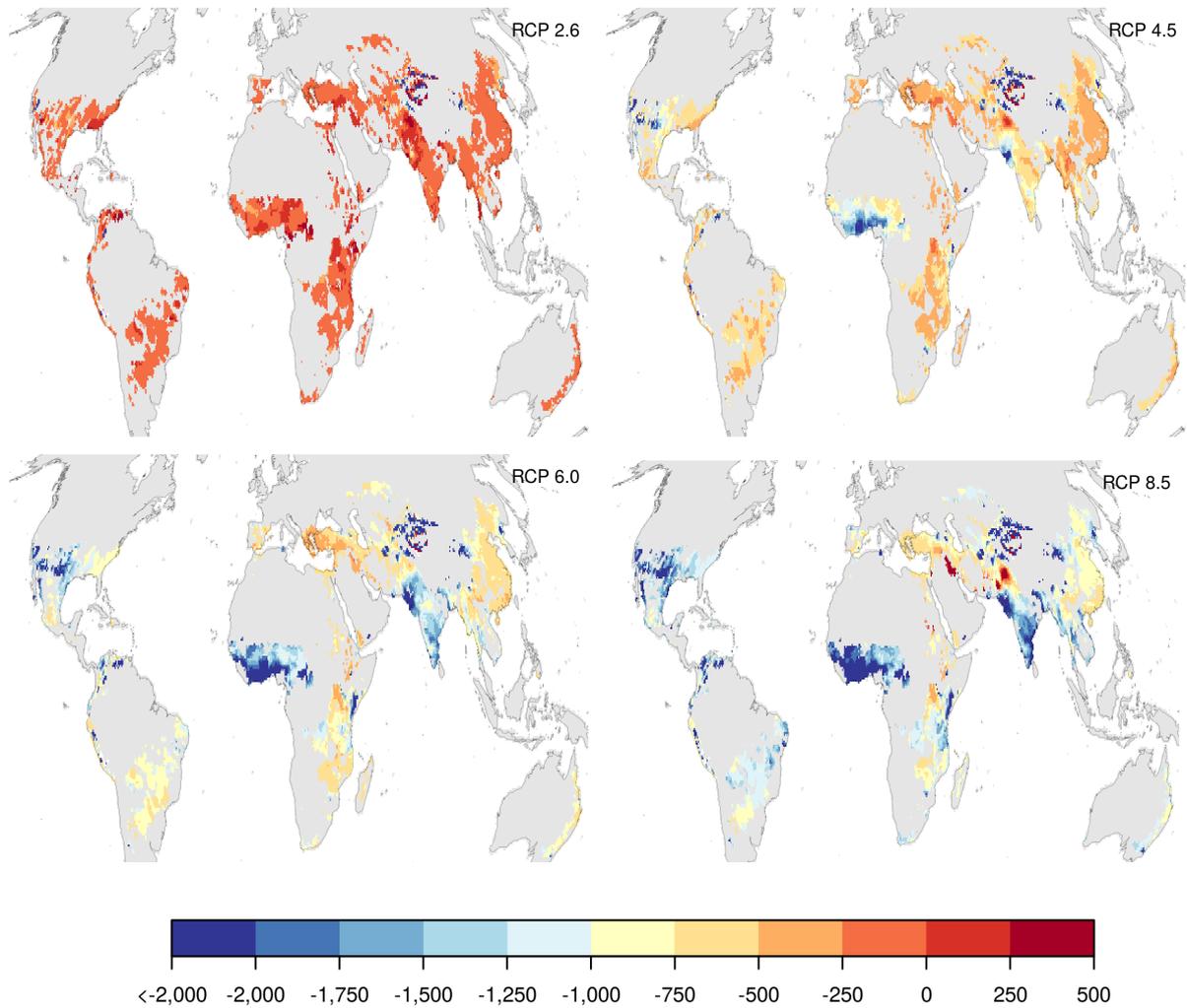
Figure 5. Simulated changes in virtual water content of seed cotton [m^{3}t^{-1}] for different RCPs. The spatial pattern of rainfed and irrigated cotton harvested areas was kept constant at the pattern of the year 2000 as provided by Portmann et al. (2010). Gray indicates areas currently not used for cotton production. Values were averaged over the 5 GCM patterns and over the period 2070-2099. Baseline period for comparison 1980-2009.

decreasing virtual water content in these regions, it increases by 2,000 m^{3}t^{-1} if the CO_2 effects are not accounted for (Figure S16). Although cotton production strongly declines if the CO_2 effect is neglected, increased VWC values clearly impinge on global water consumption of cotton production. For RCP2.6 and RCP8.5, the evapotranspiration related to cotton plantations amounts to 244 km^3 (3.7%) and 251 km^3 (6.5%) in 2100, respectively.

4 Discussion

4.1 Model performance

The model can reproduce national yield levels very well (Figure 1). This can in part be expected as we use the best performing level of deficit irrigation in the comparison as well as national planting densities and reported growing seasons. However, overall yield levels are often not very sensitive to smaller changes in irrigation levels (*full* vs. *deficit 75*) and it is plausible to assume that irrigation typically is applied in quantities that are sufficient to eliminate the majority of water stress. Also, yield levels in countries with no or little irrigation can also be well reproduced. National planting densities have been taken from literature sources and were not selected to match observed yield levels. A wide range of (national) cotton planting densities is reported in the literature, which would allow for further modification of this parameter to refine our results. However, field research has shown different effects of increasing plant density on cotton yield and understanding how cotton growth is affected by that parameter multiple interacting factors must be considered (Heitholt and Sassenrath-Cole, 2010). In this study, we therefore have selected planting densities corresponding to the lower end of the spread reported and kept these values static, but literature suggests that planting densities have changed over time, explaining part of the temporal variation in cotton yields (Venugopalan et al., 2013). Another key component is the cultivar choice as several breeding programmes developed high yielding cotton varieties well adapted to different environmental conditions (e.g. Bange and Milroy (2004); Stiller et al. (2004, 2005); Bibi et al. (2008b)).

The temporal variation in cotton yields can only partly be reproduced. This comparison is hampered by using static management assumptions in the absence of good spatially and temporally resolved management data, which is a general difficulty in evaluating gridded crop models' performance (Müller et al., 2017). The contribution of weather variability on yield levels remains unclear as the yield variability in reported yield statistics is not only affected by variability in weather, but also by varying management conditions (Schauberger et al., 2016). Ray et al. (2012) reported that only 30 % of global yield variability can be attributed to weather drivers for maize, wheat, rice and soybean and also Müller et al. (2017) found better agreement between crop model simulations and yield statistics in high-input countries, suggesting that agreement between crop model simulations and yield statistics can only be expected in countries where management conditions are stable. Larger jumps in yield statistics as e.g. in Brazil, China, India, Pakistan and several West-African countries suggest changes in management that cannot be expected to be reproduced by this modeling setup with static management assumptions (Dong et al., 2005; Venugopalan et al., 2013; Rossi et al., 2004). Additionally, inconsistencies between different data sets used to determine agricultural areas dedicated to cotton (details in Fader et al. (2015)) cause significant deviations from the annual harvested cotton areas provided by FAO et al. (2018), which was also reported as a source of uncertainty for other crops (Porwollik et al., 2017).

The good agreement with Chapagain et al. (2006) on virtual water content of cotton production adds further trust to the model simulations, as productivity and water consumption are intrinsically coupled in the model. Even though the estimates from Chapagain et al. (2006) are also model-based estimates rather than observations, the simulated patterns are plausible and have been achieved with different methods.

4.2 Implications of climate impacts

Elevated [CO_2] has been shown to increase leaf photosynthetic rates and crop radiation-use efficiency (Hileman et al., 1994; Idso and Idso, 1994; Reddy and Zhao, 2005; Broughton, 2015) and reduce transpiration at the leaf level through reduced stomatal conductance (Hileman et al., 1994; Broughton, 2015; Zhao et al., 2004), in cotton. Both effects potentially lead to improvements in growth and yield. A broad range of yield increases, averaging around 38% has been reported for cotton bolls for an increase in [CO_2] of 190 ppm (360 to 550 ppm), which is substantially stronger than the average response in most other crops, but only based on a very small set of experiments (Kimball, 2016). In line with changes in transpiration rates for canopies under elevated [CO_2], Mauney et al. (1994) reported increased water-use efficiency as a function of increasing biomass production rather than a reduction in water use in the FACE experiments. In contrast, Reddy et al. (2005b) showed that increase in temperatures above optimum decrease cotton yield due to increased boll abscission and smaller boll size. In their experiment, even a significant increase in [CO_2] did not fully compensate the negative effects on yields. The authors concluded that future increases in [CO_2] in combination with higher temperatures will decrease regional cotton yields. Likewise Reddy and Zhao (2005); Bibi et al. (2008a); Oosterhuis and Snider (2011) and Soliz et al. (2008) have shown cotton yields to be negatively impacted by elevated temperature (direct climate change). This is in line with our findings, except for Peru and Northeast-China where we find that current yields are maintained under climate change. This is likely because present temperatures are considerably below the growth optimum and evaporative demand remains comparably low in the climate change scenarios considered here. In our model simulations, CO_2 fertilization overcompensates climate-change induced yield penalties and although CO_2 effects on cotton yields are largely unclear, FACE data support a strong positive effect (Hileman et al., 1994; Idso and Idso, 1994; Reddy et al., 1999; Mauney et al., 1994; Mauney, 2016). Even though Kimball (2016) do not report any results on CO_2 fertilization effects under limited N supply, the co-limitation by nutrients is not covered here and future research should account for these effects as well as e.g. by implementing these cotton features into the model version LPJmL5.0 that was developed in parallel (von Bloh et al., 2018). As with high, above-air temperatures (above 35 °C) the abscission of bolls increased sharply with near zero retention of bolls at 40 °C (Reddy et al., 1991; Zhao et al., 2005; Reddy et al., 2005a; Luo et al., 2014b), the performance of LPJmL on cotton yields could be enhanced by introducing a yield penalty depending on high temperature, e.g. a zero boll harvest index at temperatures above 35°C. In this study, the upper optimum temperature limit constrains photosynthesis at 32 °C, indirectly inhibiting yield gain. However, decreasing crop yields caused by high temperatures are often a consequence of temperature triggered water stress (Schauberger et al., 2017; Schlenker and Roberts, 2009), which is reflected in our model by an increased crop water demand.

Cotton is a perennial, indeterminate crop and cultivated species are generally photoperiodic insensitive. Consequently, warmer temperatures will increase the rate of plant development but not necessarily reduce the length of growing season if

365 temperature seasonality is the limiting factor (Waha et al., 2012; Minoli et al., 2019) and sufficient water and nutrients are available (Bange and Milroy, 2004; Wang et al., 2008; Stiller et al., 2004; Luo et al., 2014b; Bange et al., 2016). Hence, one major effect that reduces crop yields in annual crops (Ottman et al., 2012; Asseng et al., 2015) is not as relevant for cotton. However, cotton management decisions, such as to actively shorten the season to grow cotton (Constable and Bange, 2015), were not accounted for.

370 Climate change is associated with changes in patterns of precipitation and water availability, hence, cotton plants in some regions may be subjected to plant water deficits. Water deficit limits growth and productivity of cotton plants, and the severity of the problem may increase due to changing world climatic trends (Le Houérou, 1996). Plant water deficits depend both on the supply of water to the soil and the evaporative demand of the atmosphere. Changes in atmospheric $[CO_2]$ may alter the water-use efficiency of cotton production. Cotton grown under $[CO_2]$ of 700 ppm use water more efficiently compared with plants

375 grown at a CO_2 concentration of 350 ppm (Reddy et al., 1995, 1998; Ephrath et al., 2011) because closing the stomata to reduce the transpiration rate does not impede the same penalty on carbon assimilation under elevated $[CO_2]$. Samarakoon and Gifford (1995, 1996) also found higher water use-efficiencies for cotton grown at $[CO_2]$ of 710 ppm than at ambient $[CO_2]$ (352 ppm), but demonstrated a higher plant water use compared with cotton grown at ambient $[CO_2]$ since increased biomass outpaced the water savings at leaf level. FACE experiments, however, showed no differences in total plant water use, i.e. evapotranspiration,

380 of cotton grown at 550 ppm and ambient $[CO_2]$, respectively (Dugas et al., 1994; Kimball et al., 1994; Hunsaker et al., 1994). Total water consumption (evapotranspiration) can thus be expected to respond to leaf biomass (canopy development), water use efficiency and water availability.

Our results suggest that the beneficial effects of elevated $[CO_2]$ on cotton yields overcompensate yield losses from direct climate change impacts (temperature rise, changes in precipitation). Even though experimental evidence supports strong CO_2

385 effects on cotton and it is plausible to assume that cash crops such as cotton are grown with sufficient fertiliser applications if economically feasible, several caveats remain. First, there is only very little data on cotton grown under elevated $[CO_2]$ so that the modeled response remains inherently uncertain, especially in different climate zones and at high $[CO_2]$, which typically has not been investigated in experiments. Second, negative effects of heat-days with temperatures above 35°C are not represented in the model. Possible negative effects on crop phenology, such as the shedding of leaves under heat and/or drought are not

390 sufficiently understood and are also not represented in the model. Large shares of current cotton production areas are irrigated and we find that irrigated cotton production does not suffer from climate change if CO_2 effects are considered, whereas rainfed production is more sensitive to climate change. However, climate change also affects water availability for irrigation and has thus the potential to also substantially affect agricultural production (Elliott et al., 2014). These effects are not considered here, as the ISIMIP protocol for agricultural production prescribes unlimited water supply for irrigation (Frieler et al., 2017).

395 Considering these caveats, our results need to be considered optimistic. Further research on the effectiveness of long-term and high-end CO_2 fertilization effects as well as damages from heat is necessary to better constrain results. Accounting for constraints in freshwater availability is feasible with LPJmL in further research, yet many confounding effects, such as impacts from ozone (Schauberger et al., 2019) or pests and diseases cannot be easily considered.

Overall, our simulation of climate change impacts on global cotton production results in similar patterns as for other crops. Given the economic relevance of cotton production in areas as Western Africa or South Asia, climate change (elevated temperature and water stress effects) poses an additional stress and deserves special attention. This holds particularly true as agriculture in these regions is already under pressure from increased demand for intensification considering rapid population growth. Changes in virtual water content and water demands for cotton production are of special importance, as cotton production is known for its intense water consumption that led, e.g., to the loss of most of the Aral sea (Glantz, 1999; Pereira et al., 2009).

The implications of climate impacts on cotton production on the one hand, and the impact of cotton production on water resources (with major impacts particularly in India and Uzbekistan) on the other hand illustrate the need to assess how future climate change may affect cotton production and its resource requirements. The inclusion of cotton in LPJmL allows for various large-scale studies to assess impacts of climate change on hydrological factors and its implications for agricultural production and carbon sequestration.The limited availability of data (such as valid information on tree density, irrigation management, sowing dates) substantially limits model performance and evaluation. Another issue related to data scarcity is the need for scenarios of future cropping patterns, adaptation and management as a consequence of climatic and socioeconomic change. With climate change very likely affecting the potential growing areas of cotton (such as of other agricultural crops) and their profitability, it is essential to provide crop yield estimates and associated water requirements under different climate scenarios to other research projects, e.g. on land-use change projections (Nelson et al., 2014). Analysing future cotton production may require more a detailed parameterization of cotton production, allowing for the differentiation of cotton varieties, grid-cell-specific planting densities and its differentiation between irrigated and rain-fed conditions, as well as crop-specific fruit set, which at present depends on the phenological development. The extended version of LPJmL is an important improvement as it allows for explicitly studying cotton production under climate change and associated water consumption. Results need to be carefully assessed and interpreted, as model performance remains uncertain under given constraints on data availability for model evaluation. Future work should focus on effects of climate change on irrigation water availability as well as on an implementation of heat stress effects on cotton productivity.

5 Conclusions

As most widely produced natural fiber cotton is of high importance to economies, but growth and irrigation water demand of cotton may be challenged by future climate change. To study how future cotton productivity is affected by projected climate change, we use the global biogeochemical model of hydrology, carbon exchange and crop growth, LPJmL, expanded to include cotton plants. Available data on observations and published estimates are used to validate the model and a set of climate scenarios following the ISIMIP protocol to simulate global future cotton yield and water consumption. We then analyse the global cotton production and irrigation water consumption under spatially varying present and future climatic conditions. Our results suggest that the beneficial effects of elevated [CO_2] on cotton yields overcompensate yield losses from direct climate change impacts, i.e. without the beneficial effect of [CO_2] fertilization. While changes in atmospheric CO_2 may turn into

enhanced water use or water-use efficiency of cotton production, the impact of elevated CO_2 on cotton growth depends also on plant water availability. The extended version of LPJmL is an important improvement as it allows for explicitly studying cotton production under climate change and associated water consumption. Our results should be regarded as optimistic, because of high uncertainty with respect to CO_2 fertilization and the lack of implementing processes of boll abscission under heat stress. Thus they need to be carefully assessed and interpreted, as model performance remains uncertain under given constraints on data availability for model evaluation. Future work should focus on effects of climate change on irrigation water availability as well as on an implementation of heat stress effects on cotton productivity.

Code and data availability. The model code of LPJmL4 is publicly available through PIK's GitHub repository at https://github.com/PIK-LPJmL/LPJmL and should be cited as Schaphoff (Ed.), S.; von Bloh, W.; Thonicke, K.; Biemans, H.; Forkel, M.; Gerten, D.; Heinke, J.; Jägermeyr, J.; Müller, C.; Rolinski, S.; Waha, K.; Stehfest, E.; de Waal, L.; Heyder, U.; Gumpenberger, M.; Beringer, T.: LPJmL4 Model Code. V. 4.0. GFZ Data Services. http://doi.org/10.5880/pik.2018.002, 2018. With acceptance of this manuscript, an extended, exact version of the code and the output data from the model simulations described here will be published with DOI via GFZ Data Services under https://doi.org/10.5880/Pik.2020.001 and should be referenced as Jans et al. (2020). In the meantime, the data can be accessed by reviewers via this review link:
http://pmd.gfz-potsdam.de/panmetaworks/review/9dc620caca61277d2f7a88d31af4908090b8a1720d722af866ae7e8d9946d7cc-pik. The review link will be deleted as soon as the DOI is active.

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