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

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S1 Introduction - economic background

Table S1. The top ten cotton producing countries (Sheth, 2017) and their cotton export values in 2017 (including raw cotton, cotton yarn, thread and woven fabrics) (ITC, 2019)

Country	Cotton export value [billion US$]
China	15.1
United States	7.6
India	6.9
Pakistan	3.5
Turkey	1.7
Australia	1.6
Brazil	1.5
Uzbekistan	0.9
Turkmenistan	0.4
Mexico	0.25
Total	39.45

S2 Parameterisation of cotton

S2.1 Planting density

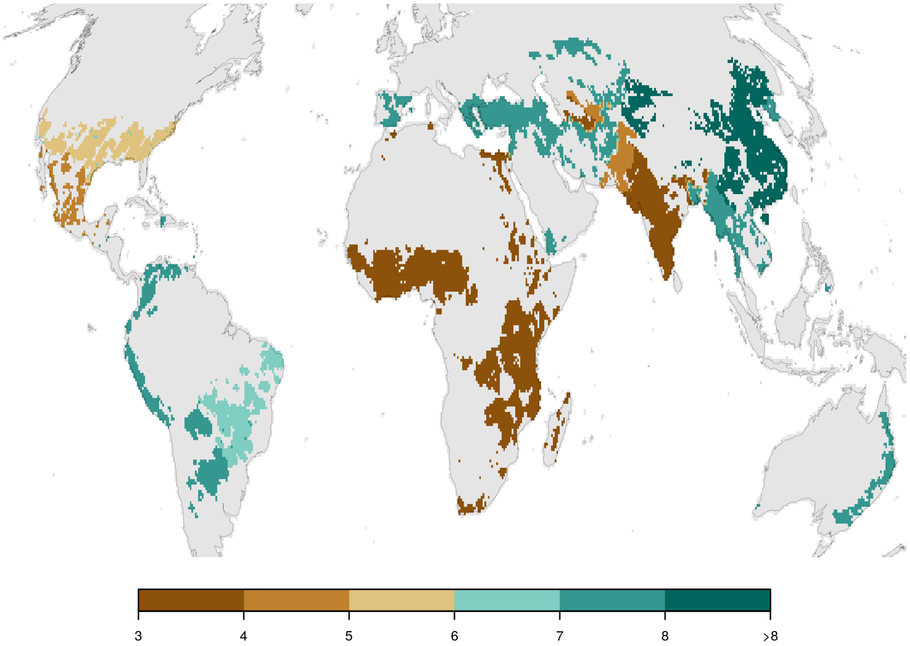
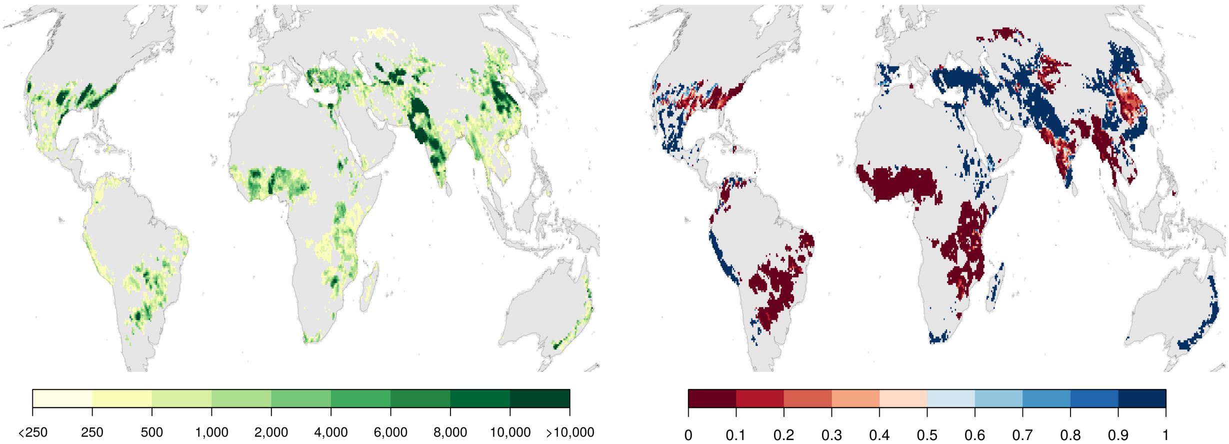


Figure S1. Country-specific cotton planting densities [plants m^{-1}] used in this study. Gray indicates areas currently not used for cotton production (Portmann et al., 2010).

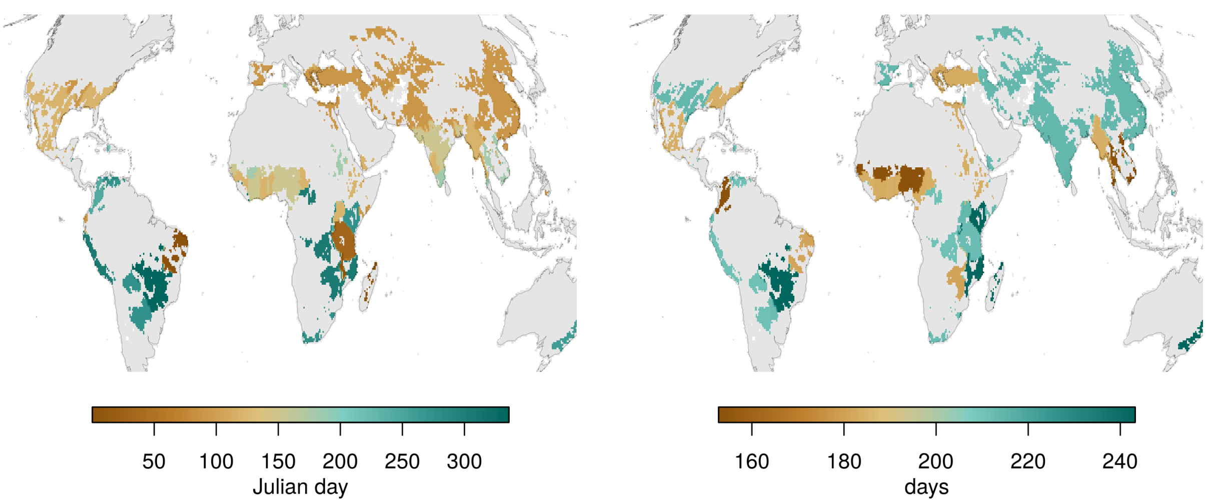
S2.2 Total cotton area and irrigated crop land fraction



(a) (b)

Figure S2. (a) Spatial distribution of cotton area [ha grid cell^{-1}] and (b) the share of irrigated area in total cotton area around the year 2000 as provided by Portmann et al. (2010). Gray indicates areas currently not used for cotton production.

S2.3 Sowing days and growing season



(a) (b)

Figure S3. (a) Sowing dates and (b) length of the growing period used to simulate cotton yields. See section "Modeling protocol and input data" (main text) for further description. Gray indicates areas currently not used for cotton production (Portmann et al., 2010).

S3 Results

S3.1 Evaluation of model performance

S3.1.1 National level

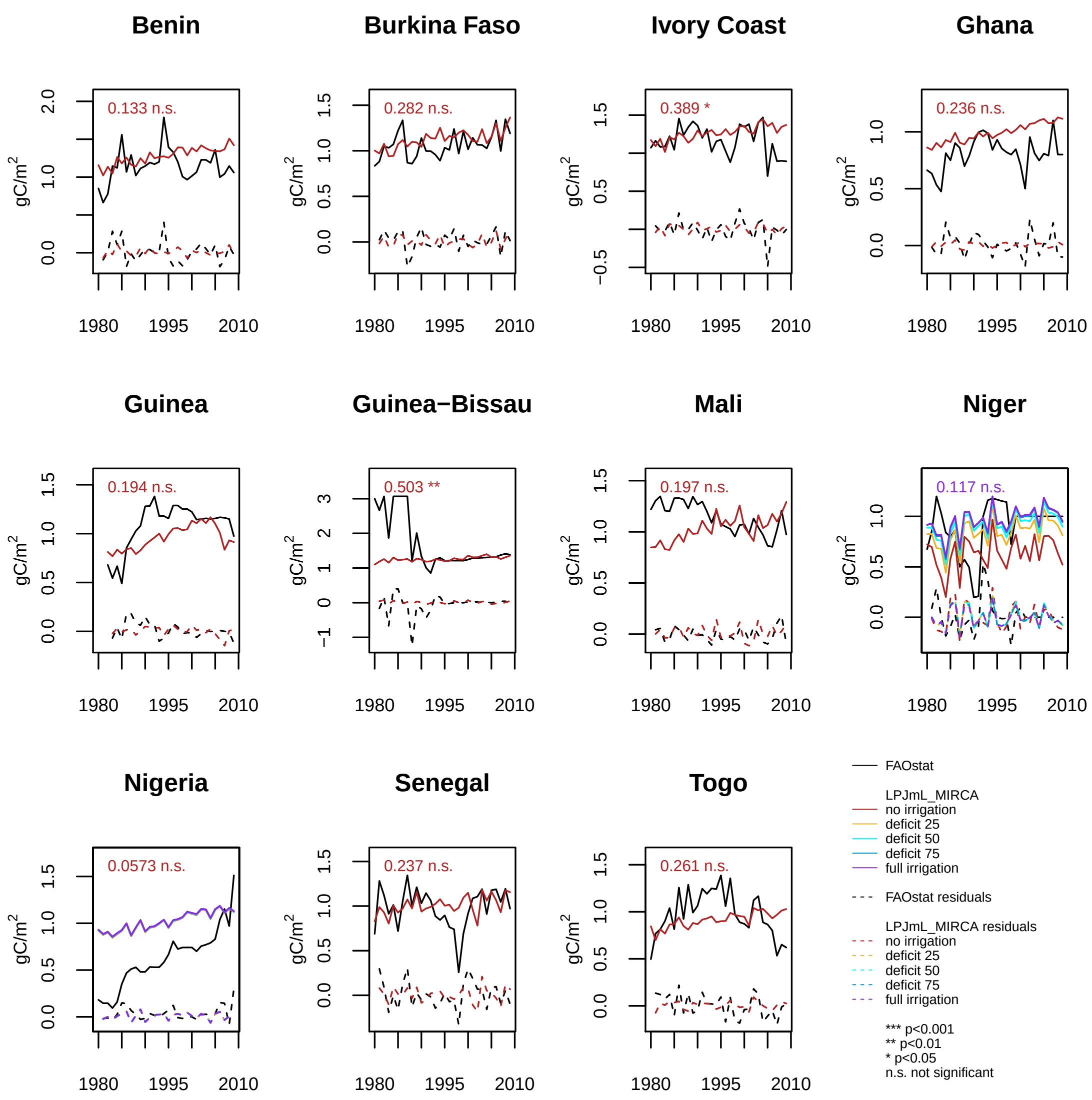


Figure S4. Comparing interannual yield variability West African countries. Numbers in each plot depict the correlation coefficient between simulated residuals and FAOstat residuals. The colour of the correlation coefficient indicates to best fitting irrigation option. The different irrigation options (on irrigated cropland only) are shown in coloured lines.

Table S2: Correlation test (Pearson method) between observed and simulated cotton yields for all cotton producing countries. Countries with missing data on either cotton area (Portmann et al., 2010) or cotton yield observations (FAO et al., 2018) were excluded.

Significance: *** p<0.001, ** p<0.01, * p<0.05, n.s. not significant

Country	Correlation	Irrigation level	MBE [t ha^{-1}]	Irrigation level	Plant density
Afghanistan	0.180 n.s.	deficit 25	0.896	deficit 25	-1
Albania	0.121 n.s.	no irrigation	0.239	no irrigation	-1
Angola	0.0818 n.s.	no irrigation	1.843	no irrigation	-1
Argentina	0.169 n.s.	no irrigation	0.669	no irrigation	-1
Australia	0.383 *	full irrigation	-0.255	deficit 75	7.5
Azerbaijan	0.425 n.s.	deficit 50	0.848	deficit 25	-1
Bangladesh	0.170 n.s.	no irrigation	-0.748	no irrigation	-1
Benin	0.133 n.s.	no irrigation	0.244	no irrigation	4
Bolivia	0.216 n.s.	no irrigation	1.751	no irrigation	-1
Brazil	0.203 n.s.	deficit 25	-0.362	no irrigation	7
Bulgaria	0.498 **	no irrigation	-0.481	no irrigation	-1
Burkina Faso	0.282 n.s.	no irrigation	0.056	no irrigation	4
Burundi	0.249 n.s.	no irrigation	0.086	no irrigation	-1
Cambodia	0.218 n.s.	no irrigation	1.521	no irrigation	-1
Cameroon	0.246 n.s.	no irrigation	0.212	no irrigation	4
Central African Republic	0.150 n.s.	no irrigation	-0.090	no irrigation	4
Chad	0.168 n.s.	no irrigation	0.725	no irrigation	4
China	0.176 n.s.	full irrigation	-0.135	deficit 25	11
Colombia	0.339 n.s.	no irrigation	-0.298	full irrigation	-1
Côte d’Ivoire	0.389 *	no irrigation	0.254	no irrigation	4
DR Congo	0.0651 n.s.	no irrigation	1.255	no irrigation	4
Ecuador	0.299 n.s.	full irrigation	0.311	deficit 25	-1
Egypt	0.349 n.s.	deficit 50	-0.121	deficit 50	-1
Ethiopia	0.153 n.s.	deficit 25	1.522	deficit 25	-1

Table S2: Correlation test (Pearson method) between observed and simulated cotton yields for all cotton producing countries. Significance: *** p<0.001, ** p<0.01, * p<0.05, n.s. not significant *(continued)*

Country	Correlation	Irrigation level	MBE [t ha^{-1}]	Irrigation level	Plant density
Ghana	0.236 n.s.	no irrigation	0.244	no irrigation	3
Greece	0.272 n.s.	deficit 25	0.047	deficit 50	-1
Guatemala	0.362 n.s.	no irrigation	1.119	no irrigation	-1
Guinea	0.192 n.s.	no irrigation	-0.018	no irrigation	3
Guinea-Bissau	0.503 **	no irrigation	0.009	no irrigation	4
Haiti	0.219 n.s.	no irrigation	1.700	no irrigation	-1
Honduras	0.381 *	full irrigation	1.208	deficit 25	-1
India	0.424 *	no irrigation	0.022	deficit 50	3.5
Iran	0.181 n.s.	deficit 75	0.092	deficit 25	-1
Iraq	0.345 n.s.	full irrigation	0.091	deficit 25	-1
Israel	0.311 n.s.	full irrigation	-0.119	full irrigation	-1
Kazakhstan	0.535 *	full irrigation	0.035	deficit 25	-1
Kenya	0.284 n.s.	full irrigation	1.092	no irrigation	-1
Kyrgyzstan	0.322 n.s.	deficit 25	0.010	deficit 75	-1
Laos	0.238 n.s.	deficit 25	0.229	deficit 25	-1
Macedonia	0.567 *	deficit 50	0.796	deficit 25	-1
Madagascar	0.374 *	full irrigation	2.956	deficit 25	-1
Malawi	0.524 **	no irrigation	-0.609	no irrigation	-1
Mali	0.197 n.s.	no irrigation	0.053	no irrigation	4
Mexico	0.227 n.s.	deficit 25	-1.140	full irrigation	5
Morocco	0.283 n.s.	deficit 25	-0.153	deficit 25	-1
Mozambique	0.0011 n.s.	no irrigation	2.550	no irrigation	-1
Myanmar	0.101 n.s.	no irrigation	1.011	no irrigation	-1
Namibia	0.413 n.s.	deficit 75	1.243	deficit 25	-1
Nepal	0.239 n.s.	no irrigation	1.610	no irrigation	-1
Niger	0.117 n.s.	full irrigation	-0.016	deficit 75	5
Nigeria	0.0608 n.s.	no irrigation	0.276	deficit 25	4

Table S2: Correlation test (Pearson method) between observed and simulated cotton yields for all cotton producing countries. Significance: *** p<0.001, ** p<0.01, * p<0.05, n.s. not significant *(continued)*

Country	Correlation	Irrigation level	MBE [t ha^{-1}]	Irrigation level	Plant density
North Korea	0.117 n.s.	deficit 25	0.670	deficit 25	-1
Pakistan	0.255 n.s.	full irrigation	-0.054	full irrigation	4.5
Paraguay	0.207 n.s.	no irrigation	2.253	no irrigation	-1
Peru	0.392 *	deficit 75	-0.045	deficit 50	-1
Philippines	0.222 n.s.	no irrigation	2.286	no irrigation	-1
Senegal	0.237 n.s.	no irrigation	-0.016	no irrigation	4
Somalia	0.194 n.s.	deficit 75	-0.404	no irrigation	-1
South Africa	0.312 n.s.	deficit 25	0.176	deficit 25	-1
South Korea	0.0296 n.s.	no irrigation	2.048	no irrigation	-1
Spain	0.300 n.s.	full irrigation	0.259	deficit 50	-1
Sudan	0.0659 n.s.	deficit 25	0.109	deficit 25	-1
Swaziland	0.523 **	no irrigation	-0.538	no irrigation	-1
Syria	0.440 *	full irrigation	-0.155	full irrigation	-1
Tajikistan	0.300 n.s.	deficit 25	0.537	deficit 25	-1
Tanzania	0.00818 n.s.	no irrigation	1.062	no irrigation	-1
Thailand	0.160 n.s.	no irrigation	0.409	no irrigation	-1
Togo	0.267 n.s.	no irrigation	0.169	no irrigation	3
Tunisia	0.00229 n.s.	no irrigation	-0.433	no irrigation	-1
Turkey	0.274 n.s.	deficit 25	-0.361	full irrigation	8
Turkmenistan	0.353 n.s.	deficit 25	0.183	deficit 50	4
Uganda	0.0159 n.s.	no irrigation	2.643	no irrigation	-1
United States	0.494 **	deficit 75	0.075	deficit 75	6
Uzbekistan	0.403 *	deficit 50	0.033	deficit 75	4.5
Venezuela	0.401 *	no irrigation	-0.659	no irrigation	-1
Vietnam	0.198 n.s.	no irrigation	0.484	no irrigation	-1
Yemen	0.221 n.s.	deficit 25	0.706	deficit 25	-1
Zambia	0.381 *	no irrigation	1.480	no irrigation	-1

Table S2: Correlation test (Pearson method) between observed and simulated cotton yields for all cotton producing countries. Significance: *** p<0.001, ** p<0.01, * p<0.05, n.s. not significant *(continued)*

Country	Correlation	Irrigation level	MBE [t ha^{-1}]	Irrigation level	Plant density
Zimbabwe	0.622 ***	full irrigation	1.664	no irrigation	-1

S3.1.2 Grid cell level

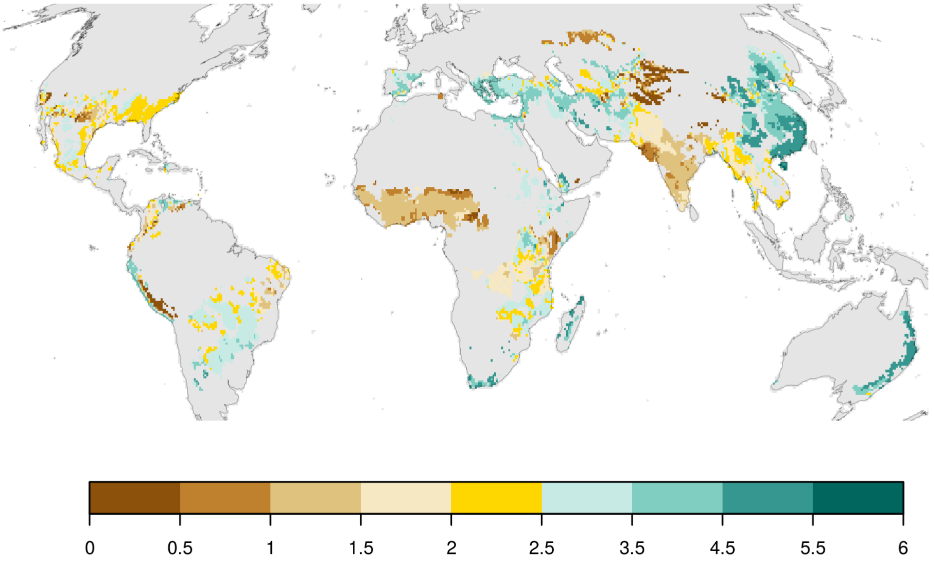


Figure S5. Simulated seedcotton yield [t ha^{-1}] on cotton production areas around the year 2000 as provided by Portmann et al. (2010). Gray indicates areas currently not used for cotton production. Yields were averaged over 1996-2005.

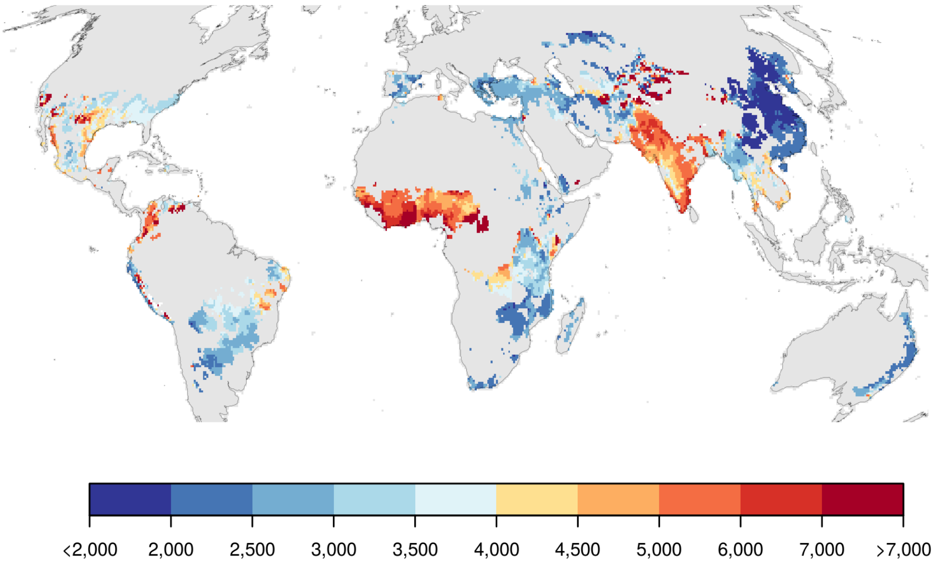


Figure S6. Simulated virtual water content of seed cotton yield [$m^3\ t^{-1}$] according to the spatial pattern around the year 2000 as provided by Portmann et al. (2010). Gray indicates areas currently not used for cotton production. Results were averaged over 1997-2001 for comparison with values in (Chapagain et al., 2006).

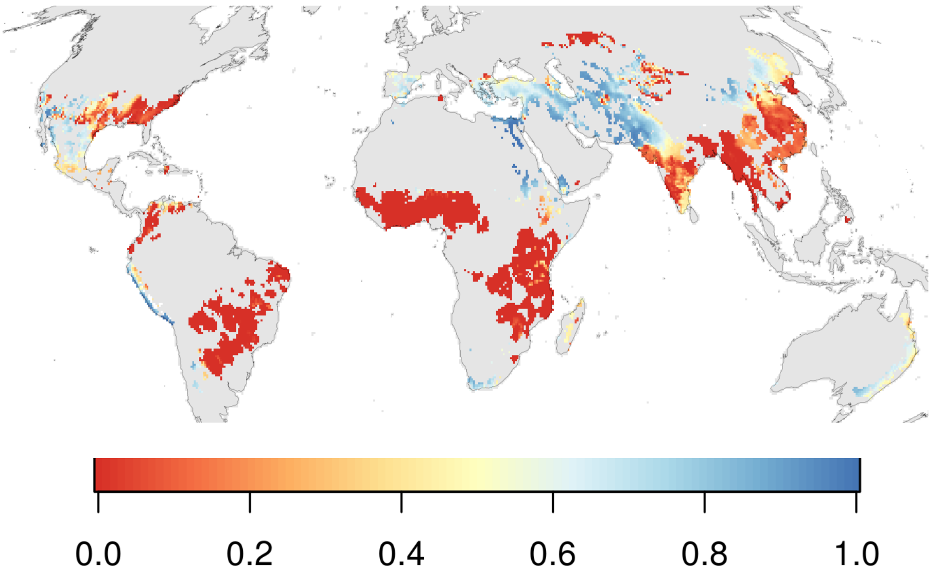


Figure S7. Ratio of blue water to virtual water content of cotton production according to the spatial pattern of irrigated cotton area shares as provided by Portmann et al. (2010). Gray indicates areas currently not used for cotton production.

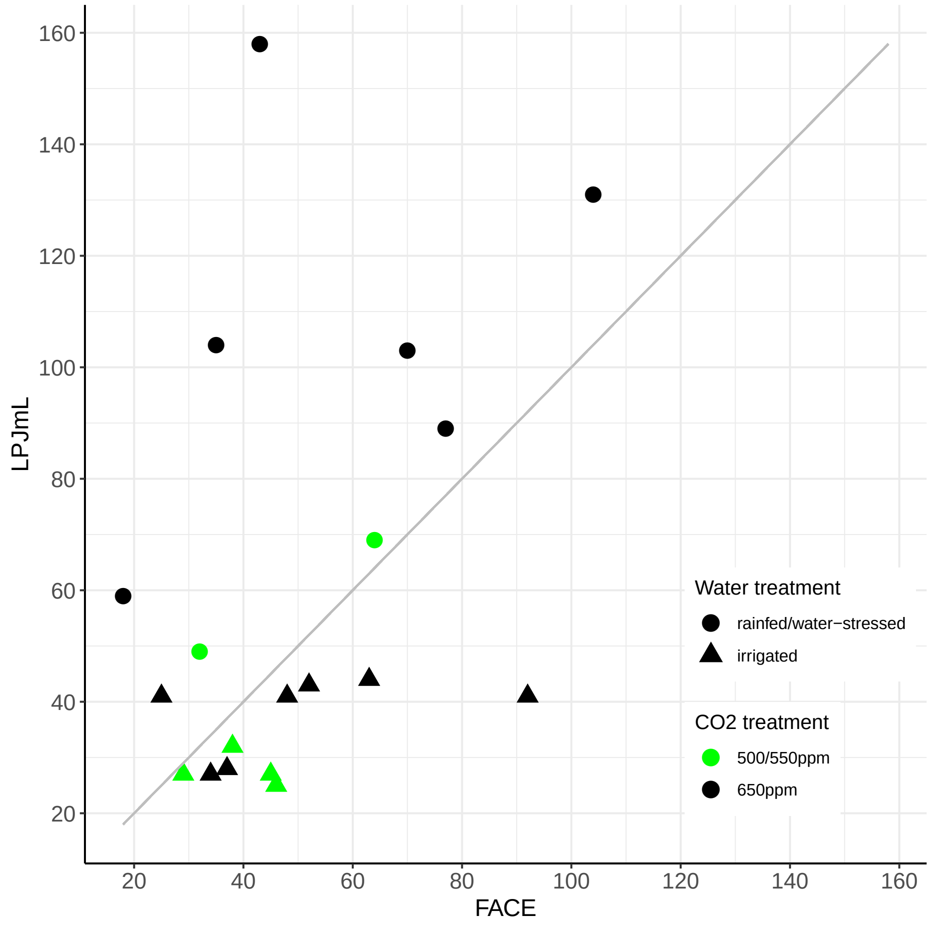


Figure S8. Relative increase in cotton yields according to increasing atmospheric CO_2 and different levels of water stress. Between 1983 and 1987 OTC technology was used to expose cotton crops to 650 µmol mol^{-1} CO_2 and results were compared to an ambient CO_2 concentration of 350 µmol mol^{-1} Kimball et al. (1992). In 1990 and 1991, FACE treatment increased atmospheric CO_2 levels starting from 353 µmol mol^{-1} (Kimball, 2016) and 370 µmol mol^{-1} (Mauney et al., 1994) to 550 µmol mol^{-1}, respectively. Simulated values (LPJmL) represent cotton yields under purely rainfed conditions and the absence of water stress, respectively. In order to reproduce some of the experimental conditions, simulation parameters such as sowing day, growing period, atmospheric CO_2 concentration and plantation density were adapted to the values provided by Kimball et al. (1992), Lewin et al. (1994) and Nagy et al. (1994). Yield data were taken from Kimball et al. (1992) for OTC yields in the years 1983-1987 and from Mauney et al. (1994) and Kimball (2016) for FACE experiments in the years 1990-1991. OTC experiments were conducted in Phoenix, Arizona (33°4'N 112°0' W) and FACE experiments in Maricopa, Arizona (33°3'N 112°3' W) and simulated results are only given for the corresponding grid cell.

S3.2 Climate change impacts on cotton production

S3.2.1 Climate change and CO_2 fertilisation

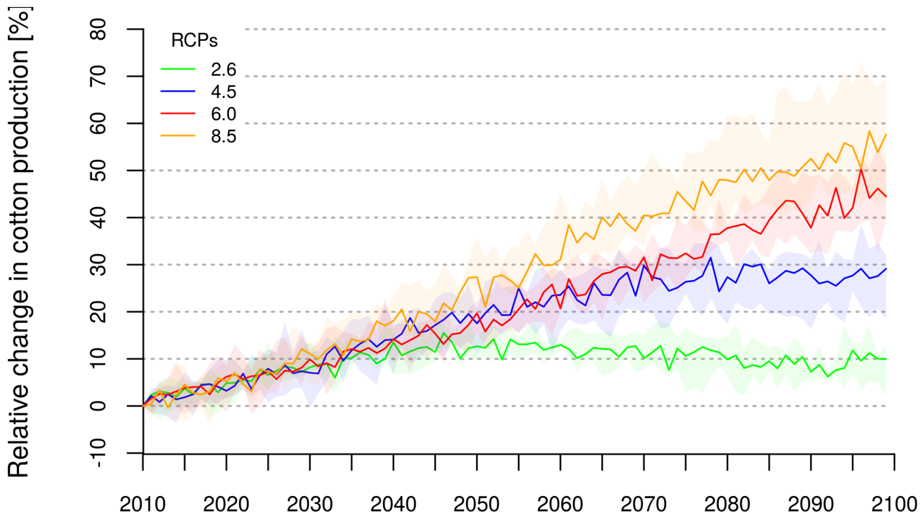


Figure S9. Relative change in LPJmL–simulated global seedcotton production [%] for different RCPs. Transparent colours show the uncertainty ranges of 5 different GCM patterns.

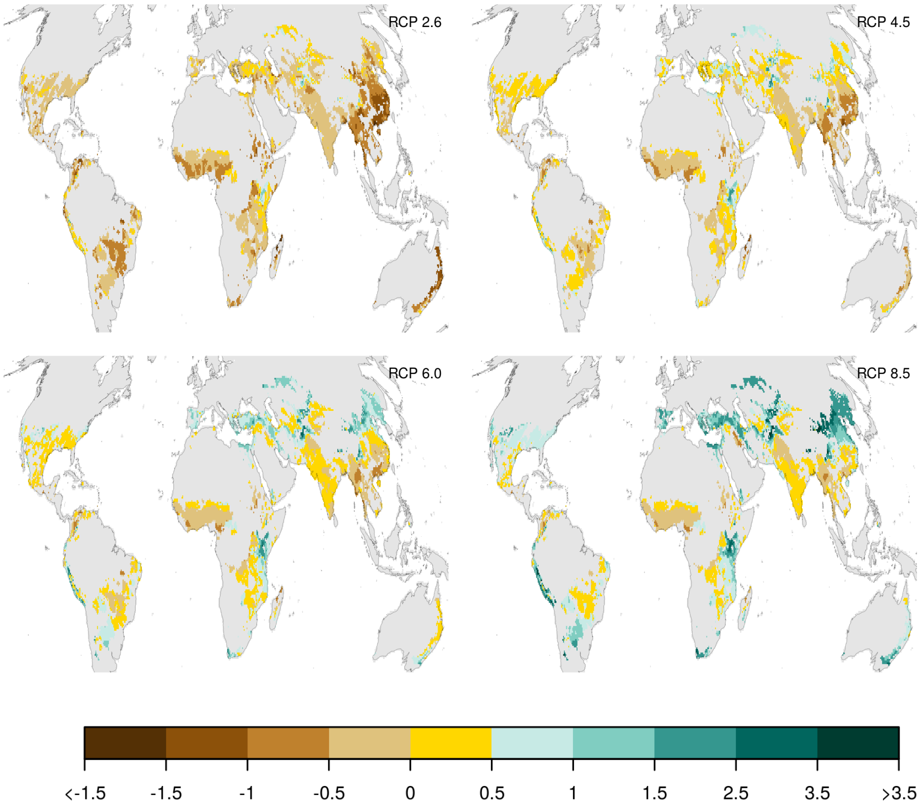


Figure S10. Simulated changes in cotton yield [t ha^{-1}] for different RCPs. Spatial pattern was kept constant to the year 2000 as provided by Portmann et al. (2010). Gray indicates areas currently not used for cotton production. Yields were averaged over 5 climate scenarios per RCP and over the period 2090-2099.

S3.2.2 Climate change without beneficial CO_2 effect

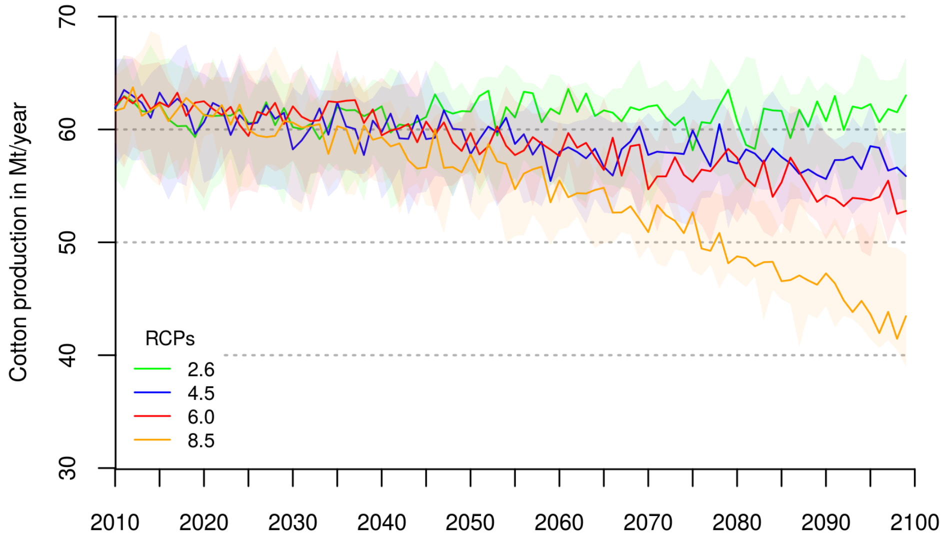


Figure S11. Simulated global cotton production [million tonnes] for different RCPs. Transparent colours show the uncertainty ranges of 5 different GCM patterns. After 2000, the [CO_2] was kept constant at the level of 2000 (368.87 ppm).

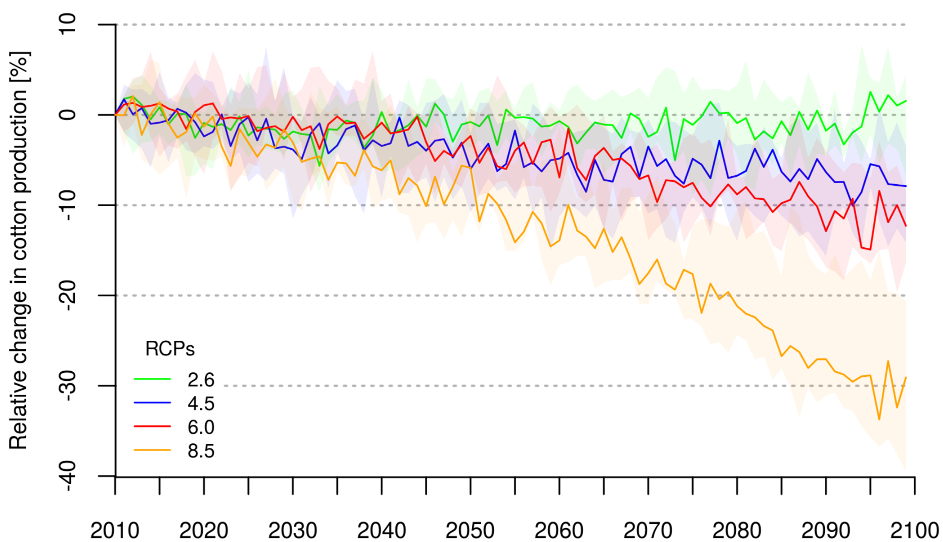


Figure S12. Relative change in LPJmL–simulated global cotton production [%] for different RCPs. Transparent colours show the uncertainty ranges of 5 different GCM patterns. After 2000, the [CO_2] was kept constant at the level of 2000 (368.87 ppm).

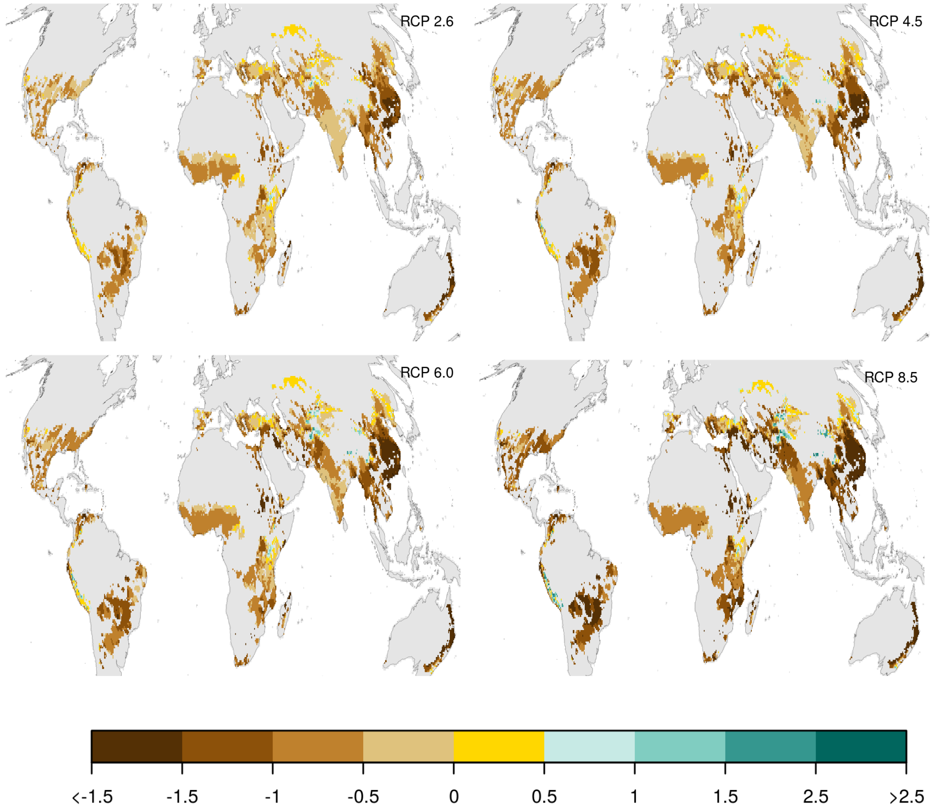
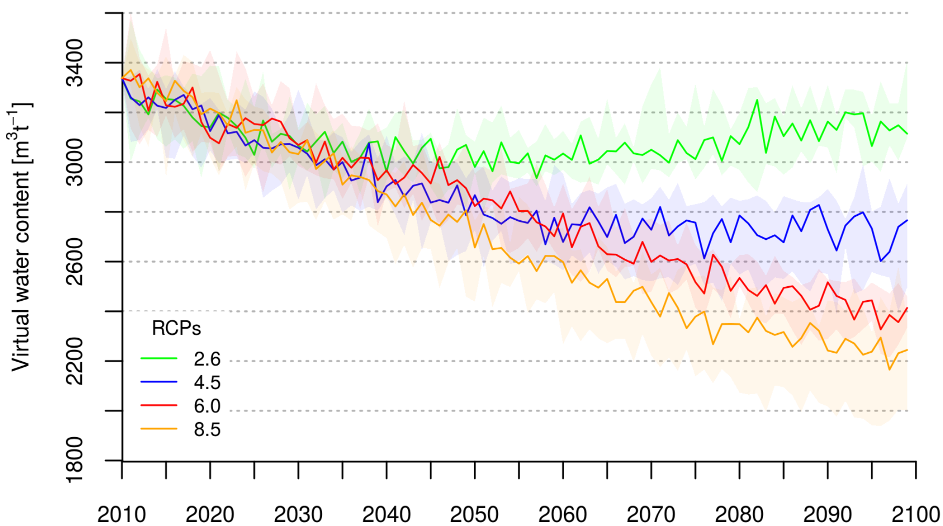


Figure S13. Simulated changes in cotton yield [t ha^{-1}] for different RCPs. The spatial cropland pattern was kept constant to the year 2000 as provided by Portmann et al. (2010). Gray indicates areas currently not used for cotton production. Yields were averaged over 5 climate scenarios per RCP and over the period 2090-2099. After 2000, the [CO_2] was kept constant at the level of 2000 (368.87 ppm).

S3.3 Climate change impacts on irrigation water consumption

S3.3.1 Climate change and CO_2 fertilisation



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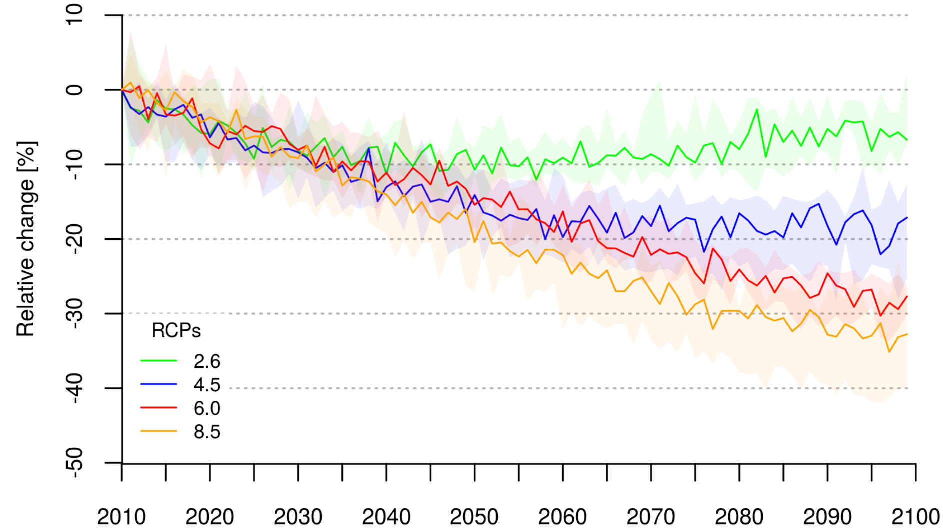
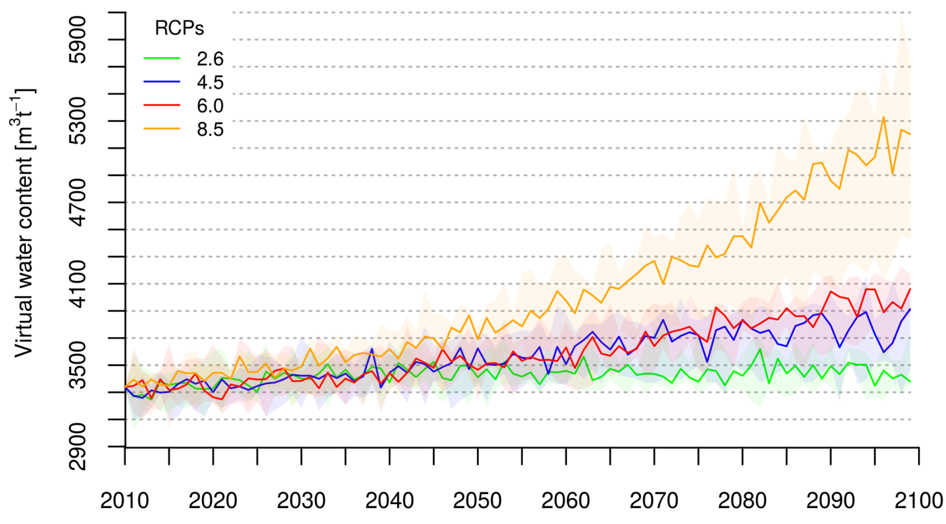


b

Figure S14. (a) Simulated average virtual water content of seed cotton [m^3t^{-1}] and (b) its relative change [%] for different RCPs. Transparent colours show the uncertainty ranges of 5 different GCM patterns.

S3.3.2 Climate change without beneficial CO_2 effect



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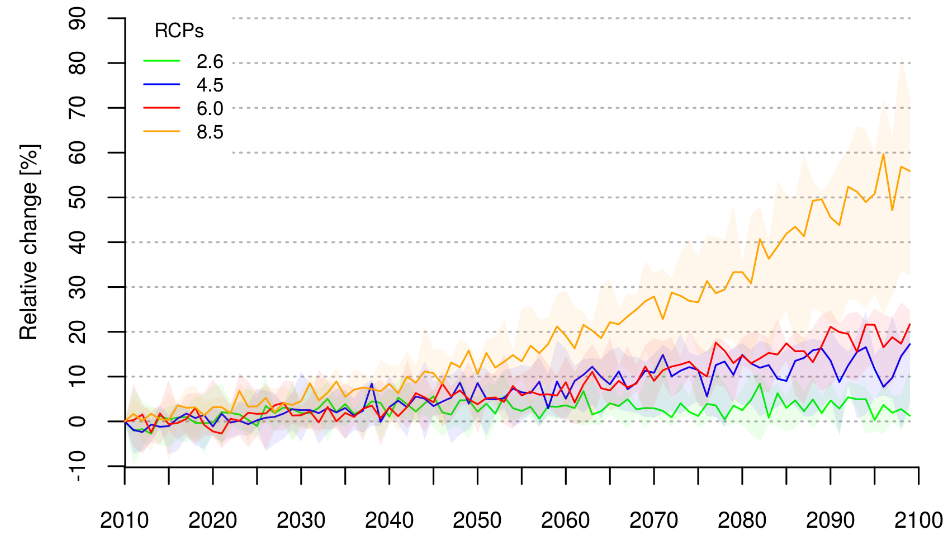

b

Figure S15. (a) Simulated average virtual water content of seed cotton [m^3t^{-1}] and (b) its relative change [%] for different RCPs. Transparent colours show the uncertainty ranges of 5 different GCM patterns. After 2000, the [CO_2] was kept constant at the level of 2000 (368.87 ppm).

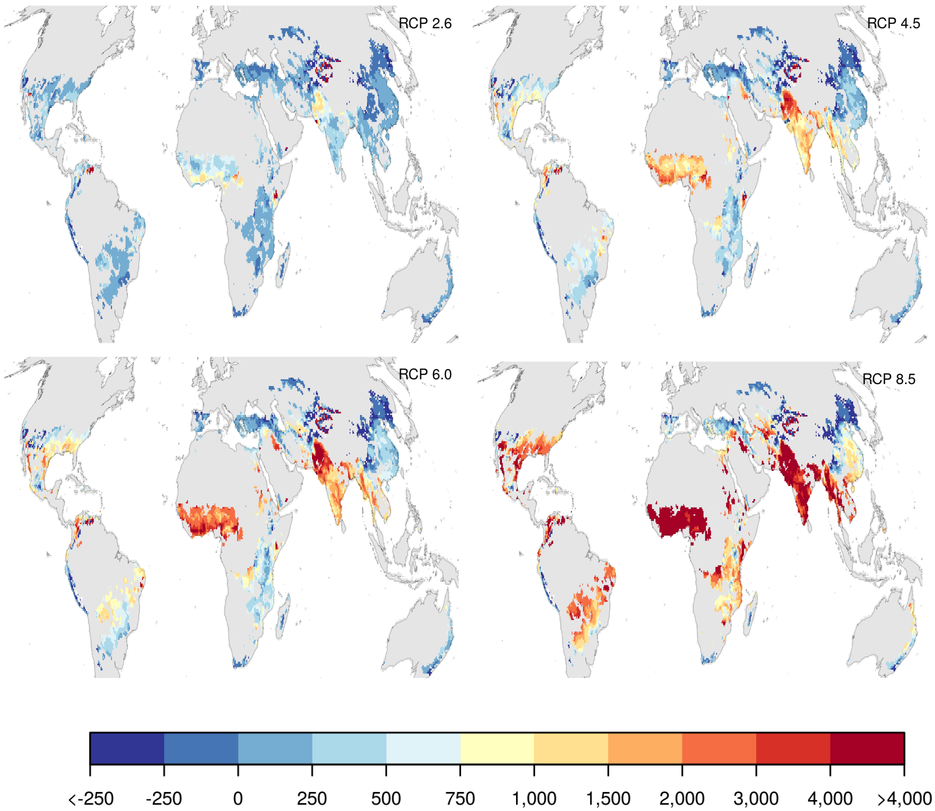

Figure S16. Simulated changes in virtual water content of seed cotton [m^3t^{-1}] for different RCPs. Spatial pattern was kept constant to the year 2000 as provided by Portmann et al. (2010). Gray indicates areas currently not used for cotton production. Yields were averaged over 5 GCM patterns and over the period 2090-2099. After 2000, the [CO_2] was kept constant at the level of 2000 (368.87 ppm).

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