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SUPPLEMENTARY INFORMATION

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Regional disparities in the beneficial effects of rising CO_2 concentrations on crop water productivity

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Supplementary Results

Global response

Table 1:

- CC w/o CO_2 affects global average crop yield and CWP negatively, with larger decreases simulated for rice and soybean;
- CC w/ CO_2 has a strong positive effect on yield and CWP, especially in the case of wheat. Positive effects on CWP of rice, soybean and maize are also large: global average CWP increases by a median 9.7, 18.2 and 13%, respectively.

Comparison to FACE observations

Figure 1: Comparison of simulated CO_2 response against FACE measurements: We extracted results from pixels corresponding to seven FACE locations (Table S1) in 2050 ([CO_2]±550ppmv) and quantified relative change in CWP under CC w/ CO_2 and CC w/o CO_2 to compare to FACE results. The comparison between simulations w/ and w/o CO_2 effects is similar to the FACE setting, but simulations compare CO_2 effects at future climate while FACE compares CO_2 effects at current climate. Irrigated sites assume no water limitation and thus only differ in temperatures. Results should not be considered as a direct comparison but just to demonstrate differences between GGCMs and a comparison of observed vs simulated CWP ranges. Supplementary Table S2 summarises nitrogen fertiliser application rates for each GGCM at each FACE location.

Overall, CO_2 effects simulated in GGCMs are slightly overestimated for maize and soybean, whilst they are underestimated for wheat and rice. We plotted simulated against observed results to assess the spread of model simulations and observations in FACE experiments (Figure S4). We find systematic biases in some models. For example, LPJ-GUESS tends to overestimate yield response of C_3 crops, while GEPIC tends to underestimate yields. This difference can partly be attributed to model features, such as photosynthesis mechanisms or parameterisations (see below) and calls for a more in depth testing of model structure and response. We note that large scale evaluation and testing of model performance against observations have been very minimal; rather, evaluation has tended to focus on yield levels, with less attention paid to the accompanying ET. This is largely because measuring crop ET over the entire growing season is extremely challenging from a technical and financial aspect.

Figure S1, S2 and S3:

Maize: Data from one site: Germany

- There is a distinct pattern of effects on yield across the models, with similar response occurring with: EPIC & GEPIC; LPJmL & LPJ-GUESS; and pDSSAT & PEGASUS. Both LPJmL and LPJ-GUESS use the PR approach, which appears here to simulate no effect of CO_2 on yield. All the RUE type models, however, show a net increase in yield. CO_2 response in pDSSAT and PEGASUS was parameterised against more recent FACE data, resulting in a similar response in yield contrasting with the EPIC and GEPIC models. EPIC & GEPIC show the largest increase, which is greater than observation. As well, pDSSAT and PEGASUS use the same equation for ET, following Priestley-Taylor, whilst the EPIC models follow the Penman-Monteith equation.

- There are differences in ET response among the models, but there is no clear pattern across modelling approach. Differences in yield and ET responses compensate each other so that GGCMs show fairly similar increases in CWP around a median 14.4%, except for LPJmL, which shows a lower increase in CWP that is closer to FACE observations (-3, 8 and 10% depending on the year of measurement (see Manderscheid et al. (2012)).

- In the case of rainfed simulations (note that the dry FACE condition is artifical and thus this set of simulations does not offer a suitable comparison), we can identify some differences between EPIC/GEPIC, LPJ-GUESS/LPJmL and pDSSAT/PEGASUS possibly due to differences in soil water balance methods affecting soil water stress and thus crop growth (e.g. rooting profile, soil layers) but further testing is necessary to confirm this.

Wheat: Data from three sites (Arizona, Australia and Germany)

1. Arizona (USA):
    - Overall, we find larger differences in yield and CPW response among models for wheat than for maize, with a much greater sensitivity to elevated CO_2 for PR models (LPJmL & LPJ-GUESS).
    - Rainfed: PEGASUS shows the smaller responses, whilst response for the point-specific models are closer to each other (with larger range for the EPIC/GEPIC models than for pDDSAT).
    - Irrigated: EPIC (18%) and GEPIC (3%) differences in response are quite large; PEGASUS shows greater response on yield (median 25%)and LPJ-GUESS much greater response (>60%) resulting in both models simulating an net increase in AET despite the overall improvement in CWP.
    - Responses in ET differ most for irrigated conditions whilst are surprisingly similar for rainfed conditions. Rainfed conditions show no response in ET for both simulations and observations whilst irrigated conditions show small decreases for EPIC, GEPIC and LPJmL, also supported by the FACE observations.
    - Responses in CWP differ largely for rainfed conditions (due to differences in yield response): (1) EPIC/GEPIC and pDSSAT exhibiting responses closer to observations (slightly above 20% in the median); (2) the LPJ models simulate much higher response (over 40%); (3) whereas PEGASUS simulates the lowest response (<10% for rainfed).
    - We also find that GGCMs respond differently to water stress, resulting in: (1) amplification of the positive effects under rainfed conditions relative to irrigated conditions for GEPIC, LPJmL and pDSSAT; (2) a decrease in the positive effects for EPIC, LPJ-GUESS and PEGASUS.
2. Australia:
    - Results show an overall increase in yield response for all GGCMs except for PEGASUS.

- Rainfed: (1) increases the positive effects relative to irrigated condtions for EPIC, GEPIC, LPJ-GUESS and pDSSAT; (2) reduce the positive effects for LPJmL and PEGASUS.
- Irrigated: a larger response for PEGASUS, which is the closest to observation.
- For rainfed response, all GGCMs show lower response than observation - but FACE reported very large increases in CWP under rainfed, which was not measured at the Arizona-wheat site.

3. Germany:

    - Irrigated: EPIC shows no response in yield; PEGASUS shows the largest response (>20%). GEPIC, pDSSAT, LPJ-GUESS, and LPJmL exhibit a response close to the median measurement.
    - Effects on ET are much smaller for the GGCMs than for FACE.
    - Effects on CWP for LPJ-GUESS and PEGASUS are relatively close to FACE, whilst they are underestimated for EPIC, GEPIC, pDSSAT and LPJmL.

Soybean: Data from one site: Illinois (USA)
Simulated effects on CWP within the range of FACE, with fairly small spread except for EPIC, with effects ranging from <0 to 20%. ΔCWP in FACE and other GGCM average 25% (median).

- LPJ-GUESS simulates a very high response, and so does pDSSAT (to a lesser extent), which also uses the PR approach for soybean. However, LPJmL does not show a similar large response.
- Results show LPJ-GUESS and PEGASUS see an increase in AET under elevated CO_2.

Rice: Data from two sites: China and Japan

- Large differences between China (40%) and Japan (20%).
- GGCMs also simulate larger response in China, although differences across sites is not as large.
- The LPJ models simulate the larger responses in yield and CWP.
- Again, LPJ-GUESS shows a much larger response for Iwate-rice.

Figure S4 includes data at additional sites reporting only on either yield or water use, for which we could not derive data on CWP. These include one additional site for rice at Ibaraki, Japan (Zhang et al., 2013) and two additional sites for wheat at Jiangsu and Beijing, China (Liu et al., 2008, Yang et al., 2006, 2009). We also collected additional data for soybean (Morgan et al., 2005), rice (Kim et al., 2003, Shimono et al., 2008) and wheat (Cai et al., 2015, Han et al., 2015) at the sites reported in Table S1.

Regional disparities

Figure 2: Effects of CO_2 on CWP are stronger in arid and semi-arid regions, where rainfed crops take full advantage of photosynthesis stimulation and improvement in water use. Because of greater temperature stress, CWP does not increase much in tropical regions under CC w/CO_2. On the contrary, CWP increases largely in temperate and cold regions, where increases in temperature, to some extent, offer a more suitable growing environment .
Table S3: By 2080, we find CC impacts on CWP of maize and wheat grown in tropical regions exhibit the largest uncertainties when accounting for CO_2: there is no consensus in the sign of relative change in CWP, which ranges between [-25.1;7.8%] for maize and between [-33.8;31.3%] for wheat. Yet, we find CWP increases by a large amount (>13% for maize; >29% for wheat) everywhere else, with more than 80% agreement in the case of rainfed wheat.
Figure 3: This map shows: (1) a particularly large effect of elevated [CO_2] on CPW for maize in arid and semi-arid areas (e.g. Spain, California, middle east, south Africa); (2) smaller/no impact in tropical regions for maize; (3) large impacts in most of Africa and South America, and smaller effects in temperate regions for C_3 crops.

Figures S5 show areas of larger variability in CO_2 effects under rainfed conditions across the full GGCMs × GCMs ensemble for each crop. These include regions known to experience higher variability in precipitation (e.g. western sub-Saharan Africa, north-eastern Brazil, southern Africa) (Christensen et al., 2013).

Figures 4 and S6 show that larger response for LPJmL and LPJ-GUESS globally, confirming partially results from individual FACE sites. PEGASUS show the more severe impacts, which is due to strong response to extreme heat-stress which hits passed 2050. In addition, LPJ-GUESS simulates net increase in AET for soybean and rice under CC w/ CO_2, contrasting with the CC w/o CO_2 scenarios due to particularly large CO_2 stimulation on leaf area index.

Figures S8-S11 show maps – similar to those shown in Fig. 3 – of individual crop model response for maize (Fig. S8), wheat (Fig. S9), soybean (Fig. S10) and rice (Fig. S11).

Effects on water use, green and blue water consumptive use

Tables S4 and S5 show how much production and corresponding consumptive crop water use, assuming no change in rainfed and irrigated harvested areas, could be gained/lost relative to production/consumptive crop water use in 2000. Table S4 shows changes in rainfed crop production and green crop water use. For instance, we estimate global production of rainfed wheat increases by a median 8.8% in 2080 relative to 2000 when accounting for CC w/ CO_2. We further estimate rising $[CO_2]$ could contribute to a net saving of a median 55,900 Mt of wheat produced when comparing to corresponding estimates under CC w/o CO_2. This amount represents 37.6% of global rainfed wheat production in 2000. Table S4 also provides estimates of differences in crop production and consumptive water use between w/ and w/o CO_2 for 2050 and 2080, respectively. These estimates are useful to distinguish the role of CO_2 on crops from that of changes in climatic conditions. Similarly, Table S5 shows changes in irrigated crop production and corresponding blue and green crop water use relative to present-day.

Uncertainties

Figures 4 and S6 show that the larger range in simulated CWP under CC w/ CO_2 is a results of large systematic differences between models. Under CC w/ CO_2, LPJ-GUESS systematically simulates larger increases in global average yield, whilst LPJmL shows particular large decreases in AET, resulting in larger CWP increases in both cases. In the case of LPJ-GUESS simulations for rice and soybean, increases in leaf area index are very important under elevated $[CO_2]$, such that the corresponding simulated AET is larger than that under CC w/o CO_2, even though LPJ-GUESS simulates improved water use efficiency. On the opposite, PEGASUS and EPIC typically simulate net decreases in global average yield, which together with moderate transpiration reductions from elevated $[CO_2]$ result in much smaller increases or even decreases in global average CWP.

Figure S7 shows that by the 2080s (i.e. at high radiative forcing and $[CO_2]$ levels) most uncertainties (59-86%) result from differences in GGCM differences in simulation of crop response to climatic variables (excluding effects of CO_2), yet an important fraction of the overall uncertainties is caused by differences in the response to CO_2 effects (10-36%); only a small portion results from the use of different climate change scenarios (3-5%).

Table S6: The spread in relative change in global CWP doubles when including CO_2 effects, even at low $[CO_2]$. In 2020, the range (MAD) in simulated relative change in global average CWP increases from 2 to 4.8%. It increases further from 5.5 to 13.5% in 2050, and from 13.2 to 23.7% in 2080. When considering CC w/o CO_2, the range remains fairly similar when including 1 GGCM × 5 GCMs or 5 GGCMs × 1GCM. As $[CO_2]$ increases, the range grows rapidly under CC w/ CO_2: it more than doubles at $[CO_2]$= 450ppmv and multiplies by a factor of 5 at $[CO_2]$= 800 ppmv. Finally, the range of simulated responses remains much smaller under CC w/o CO_2.

Supplementary Tables

Table S1: Summary table of relative change in CWP at ambient and elevated [CO_2] for FACE observations and GGCM simulations. ΔCWP values for the GGCM and for the Illinois soybean FACE site are reported as median [min;max]. All other values are actual observation reported in the corresponding reference. For the German wheat FACE site, ΔCWP values are estimated using results on yield (Weigel and Manderscheid, 2012) and ET (Burkart et al., 2011) (N app.: Nitrogen application - see Table S2; Low WS: Low water stress).

Crop	**Site**	**Reference**	**Ambient CO_2 (ppm)**	**Elevated CO_2 (ppm)**	**N fertiliser**	**H_2O**	**ΔCWP (%)**
Maize	Germany	Manderscheid et al. (2012)	378	550	High + bare soil	Wet	-3;8
						Dry	1;39
					High + mulch soil	Wet	10
						Dry	44
		This study	380	550	N app. vary	Irrigated	14.4[8.6;41.4]
						Rainfed (low WS)	15.3[-28.5;25.5]
Wheat	Arizona	Hunsaker et al. (1996)	370	550	High	Wet	12;15.8
						Dry	15.8; 27.8
		Hunsaker et al. (2000)	370	550	High	Wet	19.1;21.8
		Kimball et al. (1999)	360	550	Low	Wet	29
		This study	370	550	N app. vary	Irrigated	15.5[6.3;60.1]
						Rainfed	24.4[-4.2;84.9]
	Germany	Weigel and Manderscheid (2012)	380	550	High	Wet	30; 43.5
		Burkart et al. (2011)			Low		27.4; 32.3
		This study	380	550	N app. vary	Irrigated	17.3[2;30]
						Rainfed (low WS)	17.4[-8.4;30.2]
	Australia	O'Leary et al. (2015)	365	550	High	Wet	22.3; 32.3
						Dry	41
		This study	380	550	N app. vary	Irrigated	20.4[7.1;30.7]
						Rainfed	17.3[-22.8;33.1]
Rice	Iwate	Shimono et al. (2013)	365	548	High	Paddy	20
		This study	380	550	N app. vary	Irrigated	16.1[4.3;27.2]
						Rainfed (low WS)	16.1[4;30.8]
	Jiangsu	Zhu et al. (2015)	390	590	High	Paddy	39;46
		This study	380	550	N app. vary	Irrigated	20.5[13.4;47.6]
						Rainfed (low WS)	20.4[-0.4;47.6]
Soybean	Illinois	Bernacchi et al. (2006)	380	550	High	Wet	29.4[7,2;43.7]
		This study	380	550	Vary	Irrigated	26.4[-19.5;37.5]
						Rainfed	32.9[-14.1;47.1]

Table S2: Table summary of nitrogen fertiliser application rates (kg-N ha^{-1} yr^{-1}) for each GGCM at each FACE location.

Crop	Site	Coordinates	EPIC	GEPIC	LPJmL	LPJ-GUESS	pDSSAT	PEGASUS
Maize	Germany	$52^\circ 18' N, 10^\circ 26' E$	high	150	na	na	150	150
Wheat	Arizona	$33^\circ 06' N, 112^\circ 05' W$	high	63	na	na	70	63
	Australia	$36^\circ 45' S, 142^\circ 07' E$		43			64	70
	Germany	$52^\circ 18' N, 10^\circ 26' E$		165			185	210
Rice	Iwate	$39^\circ 38' N, 140^\circ 57' E$	high	110	na	na	80	na
	Jiangsu	$31^\circ 35' N, 120^\circ 30' E$		145			273	
Soybean	Illinois	$40^\circ 03' N; 88^\circ 12' W$	high	21	na	na	32	na

Table S3: Relative change in average CWP (%) in global, tropical, arid, temperate and cold climatic regions for rainfed and irrigated maize, rice, soybean and wheat. Median values across all GCMs-GGCMs combinations for $w/\ CO_2$ and $w/o\ CO_2$ simulations for the 2080s, under RCP 8.5. Numbers in brackets are the first and third quartiles, respectively. Degree of agreement in the sign of change is characterised by a background colour (orange: more than 80% agreement in a net decrease; yellow: between 60-80% agreement in a net decrease; green: between 60-80% agreement in a net increase; blue: more than 80% agreement in a net increase; clear: less than 60% agreement in the sign of change).

		Total harvest areas	Irrigated	$\Delta\text{CWP}_{\text{w/CO}_2}$		$\Delta\text{CWP}_{\text{w/oCO}_2}$	
		(1000 km^2 yr^{-1})	areas (%)	Rainfed	Irrigated	Rainfed	Irrigated
Maize	Global	1,487	20	13.3[3.1;23.9]	12.9[1.5;16.4]	-13.5[-23.4;-2]	-11.5[-18.3;-1.3]
	Tropical	346	5	-1.1[-25.1;7.8]	-4.3[-16;16.5]	-16.4[-35.1;-5.7]	-17.8[-30.2;-4.8]
	Arid	96	45	14.7[-9.3;27.7]	8[0.1;21.3]	-16.6[-27.3;-4.8]	-12.7[-19.5;-2.4]
	Temperate	456	25	13.5[2.1;23.7]	12.6[2.4;17.1]	-10[-20.5;-3.6]	-11.6[-17.5;-1.7]
	Cold	588	20	20.4[4.4;24.7]	10.6[2.8;15.2]	-11.4[-23;-4.2]	-11[-20;-3.1]
Rice	Global	1,574	62	8.2[-4.5;47.7]	10.6[0.4;48.7]	-26.2[-35.2;-16.1]	-21.1[-26.6;-12.2]
	Tropical	783	46	9[-6.7;47]	9.5[-10.3;49.5]	-27.3[-39.4;-17.6]	-19.2[-34.6;-15.8]
	Arid	102	92	13.1[-2;67]	23.2[-9.4;64.1]	-28.1[-36.8;-20.5]	-26.3[-34.5;-12.5]
	Temperate	633	74	5.2[-5.2;46.9]	12[-2;44.8]	-24.2[-34.8;-16]	-21.8[-29.8;-10.5]
	Cold	55	85	30.1[19;60]	30.5[24.4;60.2]	-7[-16.4;1.1]	-8.8[-16.8;4.7]
Soybean	Global	741	8	17.7[-8.5;42.7]	19.8[-9.2;37.9]	-26.1[-39.7;-19.2]	-26.7[-38.6;-15.2]
	Tropical	54	57	6.2[-10.9;45]	6.5[-9;37.5]	-34.1[-44.7;-29]	-29[-37.7;-20.3]
	Arid	156	1	21.7[1.3;76.3]	29.9[2.1;47.7]	-27.7[-37.3;-20.7]	-18.8[-32.5;-11.7]
	Temperate	300	7	23.6[-2.1;46.6]	20.5[-11.9;40]	-24.3[-33.3;-15.8]	-27[-40.5;-15.5]
	Cold	7	29	24.7[-9.8;39.8]	23.2[-1.6;39.5]	-24.9[-45;-12.6]	-24.3[-37.6;-13.8]
Wheat	Global	2,129	31	29.3[12.7;38.7]	20.7[-3.4;32.2]	-14.9[-20.6;-1.7]	-19.5[-29.9;-4.1]
	Tropical	278	12	1.6[-33.8;31.3]	-4.1[-32.7;44.8]	-36.1[-53.4;-24.2]	-35.5[-51;-24.9]
	Arid	361	63	48.2[24.7;55.6]	18.3[-4.6;36.8]	-6.3[-20.7;9.2]	-20[-31.1;-9.7]
	Temperate	817	33	30.2[15;36.9]	16.6[-5.6;31.7]	-10.9[-21;-1.7]	-20[-30.7;-4.6]
	Cold	896	14	29.2[14;40.8]	25.5[3.5;38.6]	-17[-23.2;-1.6]	-12.3[-31.6;4.1]

Table S4: From left to right: median changes in rainfed crop production (in 1000Mt) in 2050 and 2080 under *CC w/* CO_2 relative to 2000 ($\Delta Prod_{\mathrm{rf},2000}$); median changes in rainfed crop production (in 1000Mt) under CC /w CO_2 relative to that under CC w/o CO_2 in 2050 and 2080, respectively ($\Delta Prod_{\mathrm{rf,CO_2}}$); median changes in green crop water use of rainfed crops (in km^3) in 2050 and 2080 under *CC w/* CO_2 relative to 2000 ($\Delta WG_{\mathrm{rf},2000}$); median changes in green crop water use of rainfed crops (in km^3) under CC w/ CO_2 relative that under CC w/o CO_2 in 2050 and 2080, respectively ($\Delta WG_{\mathrm{rf,CO_2}}$). Numbers in parentheses indicate values as percentage of present-day (i.e. circa 2000) rainfed crop production and crop water use, respectively. Estimates of green crop water use of rainfed crops correspond to AET simulated under rainfed conditions on rainfed areas.

		$\Delta Prod_{\mathrm{rf},2000}$ 1000Mt (%)	$\Delta Prod_{\mathrm{rf,CO_2}}$ 1000Mt (%)	$\Delta WG_{\mathrm{rf},2000}$ km^3 (%)	$\Delta WG_{\mathrm{rf,CO_2}}$ km^3 (%)
Maize	2050	-5.8 (-1.3%)	12.0 (7.3%)	-27.2 (-9.1%)	-4.5 (-4.0%)
	2080	-32.0 (-7.7%)	38.9 (14.4%)	-57.9 (-16.9%)	-11.6 (-8.2%)
Rice	2050	7.9 (3.0%)	7.9 (17.0%)	-11.3 (-3.6%)	-1.0 (-1.0%)
	2080	-5.1 (-3.8%)	22.1 (34.6%)	-7.1 (-2.1%)	-3.2 (-2.5%)
Soybean	2050	4.7 (-0.4%)	11.8 (25.4%)	-13.1 (-4.7%)	-0.6 (-0.5%)
	2080	3.4 (-0.1%)	33.3 (54.8%)	-23.9 (-8.6%)	-2.2 (-1.1%)
Wheat	2050	26.7 (6.9%)	19.7 (17.9%)	-13.7 (-2.7%)	-1.8 (-1.3%)
	2080	33.4 (8.8%)	55.9 (37.6%)	-44.7 (-11.2%)	-6.2 (-4.8%)

Table S5: From left to right: median changes in irrigated crop production (in 1000Mt) in 2050 and 2080 under *CC w/* CO_2 relative to 2000 ($\Delta Prod_{\mathrm{ir,2000}}$); median changes in irrigated crop production (in 1000Mt) under CC w/ CO_2 relative to that under CC w/o CO_2 in 2050 and 2080, respectively ($\Delta Prod_{\mathrm{ir,CO_2}}$); median changes in blue crop water use (in km^3) in 2050 and 2080 under *CC w/* CO_2 relative to 2000 (ΔWB_{2000}); median changes in blue crop water use (in km^3) under CC w/ CO_2 relative to that under CC w/o CO_2 in 2050 and 2080, respectively (ΔWB_{CO_2}); median changes in green crop water use of irrigated crops (in km^3) in 2050 and 2080 under *CC w/* CO_2 relative to 2000 ($\Delta WG_{\mathrm{ir,2000}}$); median changes in green crop water use of irrigated crops (in km^3) under CC w/ CO_2 relative to that under CC w/o CO_2 in 2050 and 2080, respectively ($\Delta WG_{\mathrm{ir,CO_2}}$). Numbers in parentheses indicate values as percentage of present-day (i.e. circa 2000) irrigated crop production, blue and green crop water use of irrigated crops, respectively. Estimates of total blue crop water use are produced by summing up corresponding blue water (estimated as the difference between AET simulated under irrigated and rainfed conditions) in a grid-cell over total crop irrigated areas: $(AET_{ir} - AET_{rf}) \times A_{ir}$, where AET_{ir}/AET_{rf} represent AET under irrigated/rainfed conditions in the grid-cell and A_{ir} is the corresponding irrigated area in the grid-cell. Estimates of green crop water use of irrigated crops correspond to AET simulated under rainfed conditions on irrigated areas.

		$\Delta Prod_{ir,2000}$ 1000Mt (%)	$\Delta Prod_{ir,CO_2}$ 1000Mt (%)	ΔWB_{2000} km^3 (%)	ΔWB_{CO_2} km^3 (%)	$\Delta WG_{irr,2000}$ km^3 (%)	$\Delta WG_{irr,CO_2}$ km^3 (%)
Maize	2050	-4.9 (-3.0%)	1.9 (2.0%)	-4.7 (-6.7%)	-0.9 (-3.7%)	-4.1 (-10.8 %)	-1.3 (-9.7%)
	2080	-19.4 (-11.5%)	3.5 (4.4%)	-11.7 (-13.8%)	-2.2 (-7.3%)	-8.9 (-26.0%)	-5.1 (-28.9%)
Rice	2050	12.7 (3.2%)	18.7 (16.8%)	-13.2 (-3.2%)	-1.1 (-0.8%)	-4.7 (-9.3%)	-1.1 (-5.2%)
	2080	-6.2 (-1.7%)	55.2 (30.8%)	-17.8 (-3.6%)	-3.9 (-2.7%)	-10.7 (-21.6%)	-3.4 (-14.6%)
Soybean	2050	1.4 (6.1%)	1.0 (23.6%)	-0.4 (-1.8%)	0.0 (-0.4%)	0.0 (-3.1%)	-0.1 (-6.1%)
	2080	0.9 (6.4%)	2.5 (46.5%)	-1.0 (-4.3%)	-0.1 (-1.2 %)	-0.4 (-20.9%)	-0.4 (-19.6%)
Wheat	2050	2.1 (1.6%)	10.8 (16.5%)	-1.1 (-1.2%)	0.0 (-0.8%)	-12.8 (-10.3%)	-1.2 (-3.1%)
	2080	-6.8 (-3.9%)	27.0 (33.9%)	-9.3 (-7.1%)	-0.9 (-2.7%)	-26.3 (-27.4%)	-4.1 (-9.2%)

Table S6: Relative change in global CWP (%): Median and median absolute deviation (MAD) values across all GCMs–GGCMs combinations for *w/* CO_2 simulations and *w/o* CO_2 simulations.

			2020: 418 ppm		2050: 545 ppm		2085: 794 ppm	
			w/ CO_2	*w/o* CO_2	*w/* CO_2	*w/o* CO_2	*w/* CO_2	*w/o* CO_2
All Crops	All GCMs	All GGCMs	2.7 ± 5	-2.5 ± 3.1	8.2 ± 12.3	-8.6 ± 8.1	15.7 ± 25.2	-19.6 ± 12.4
	1 GCM	All GGCMs	2.6 ± 4.8	-2.6 ± 3.1	7.7 ± 13.5	-8.6 ± 6.5	11.1 ± 23.7	-19.6 ± 12.6
	All GCMs	1 GGCM	2.7 ± 2	-3 ± 2.4	9.1 ± 5.5	-9 ± 6.2	15.6 ± 13.2	-20.1 ± 10.1

Supplementary Figures

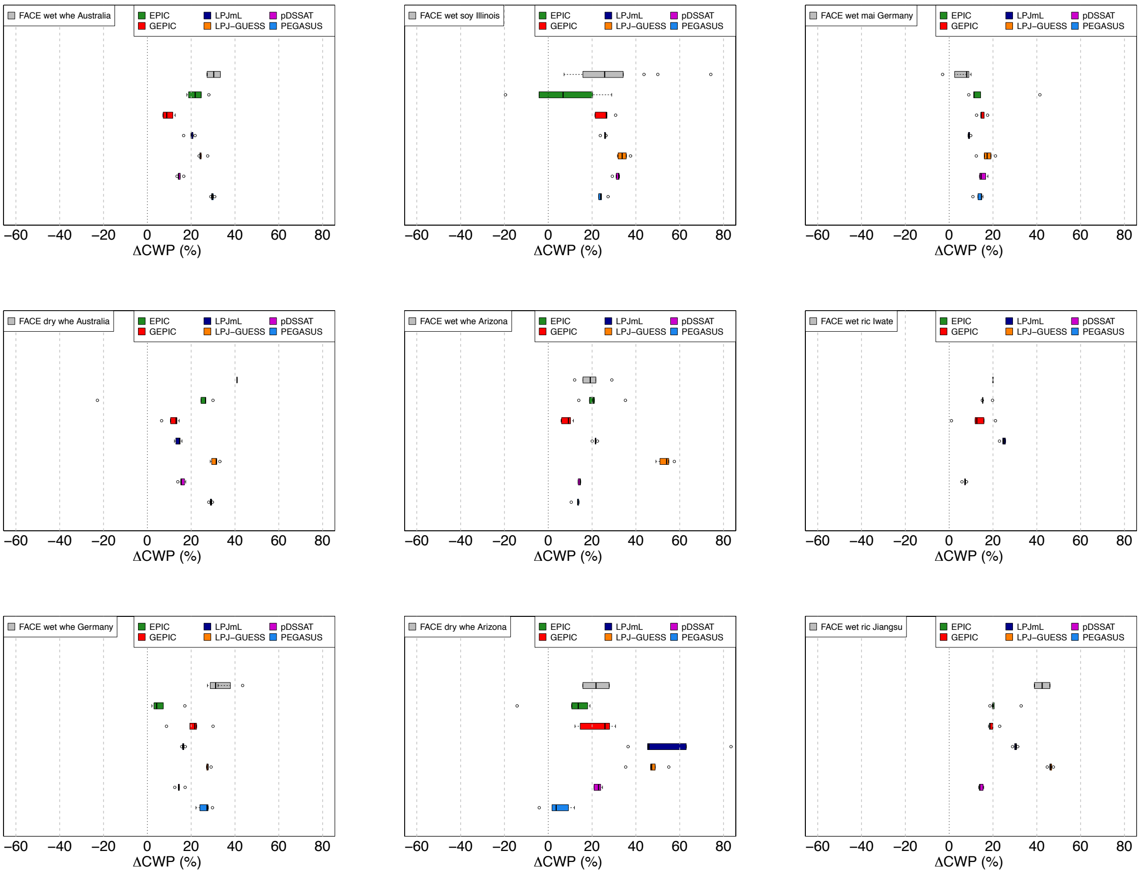

Figure S1: Individual GGCM result comparison at the seven FACE sites for ΔCWP (%), calculated as: $(CWP_e - CWP_a)/CWP_a$ where CWP_e is CWP at elevated $[CO_2]$ ($\sim$ 550ppmv) and CWP_a is CWP at ambient $[CO_2]$ ($\sim$ 380ppmv). Both wet and dry results are shown for Arizona-wheat and Australia-wheat and only wet results for the other sites (i.e. Germany-wheat; Germany-Maize; Illinois-soybean; Iwate-rice; Jiangsu-rice). The left and right sides of the box are lower and upper quartiles, respectively, and the band near the middle of the box is the median value across each set of simulations. Open circles are outliers.

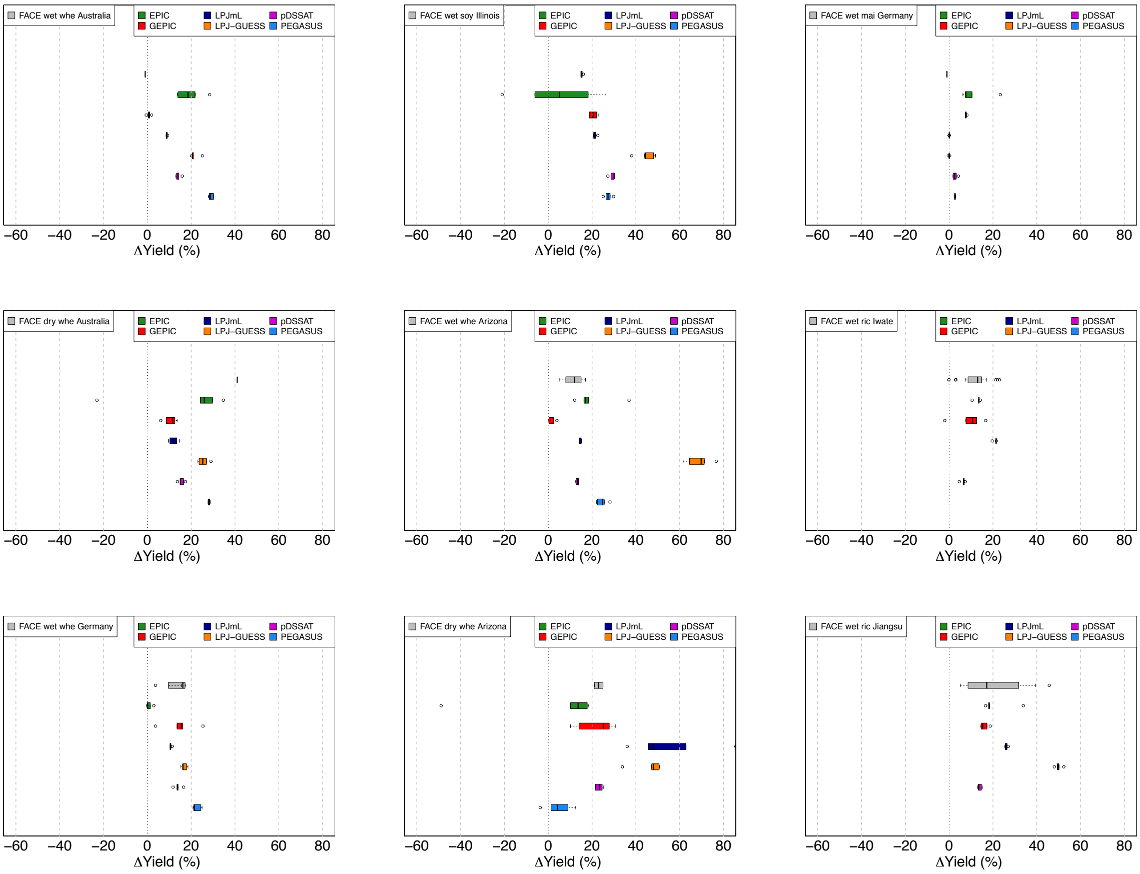

Figure S2: Same as Figure S1 for corresponding ΔYield (%).

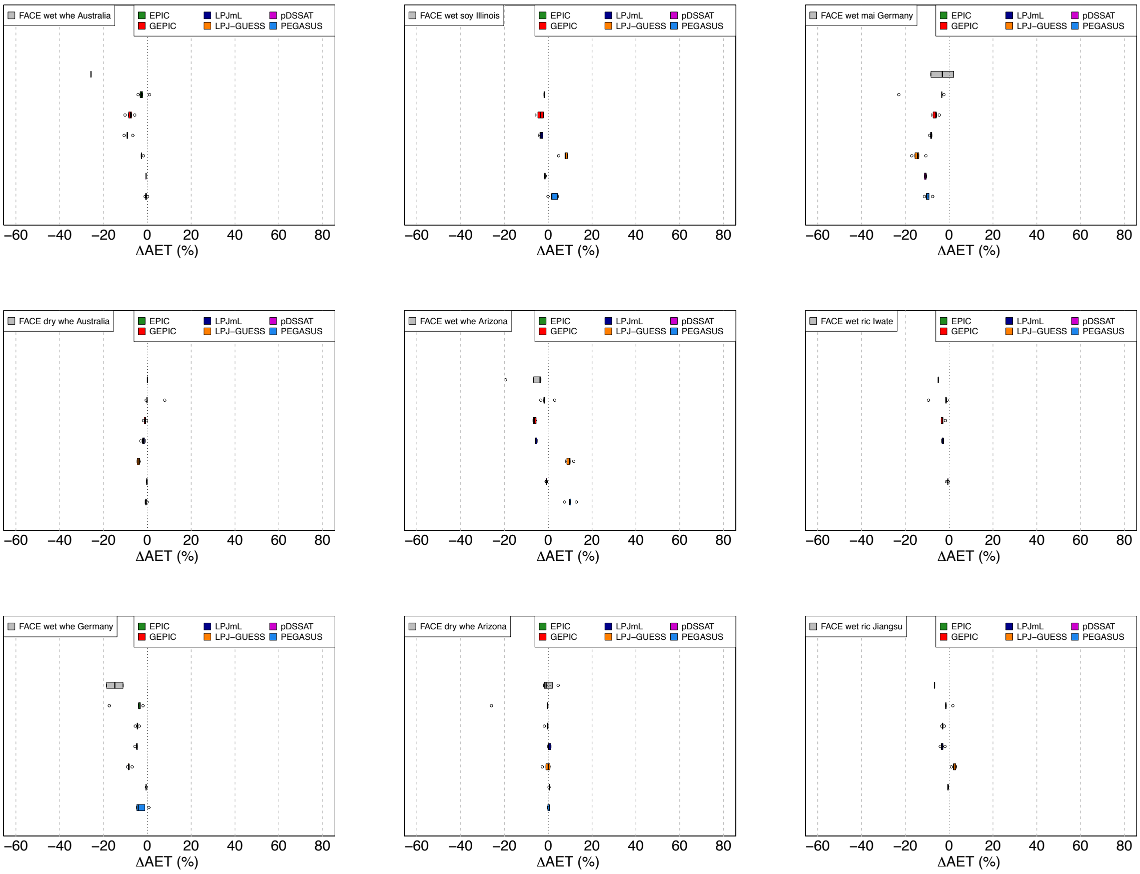

Figure S3: Same as Figure S1 for corresponding ΔAET (%).

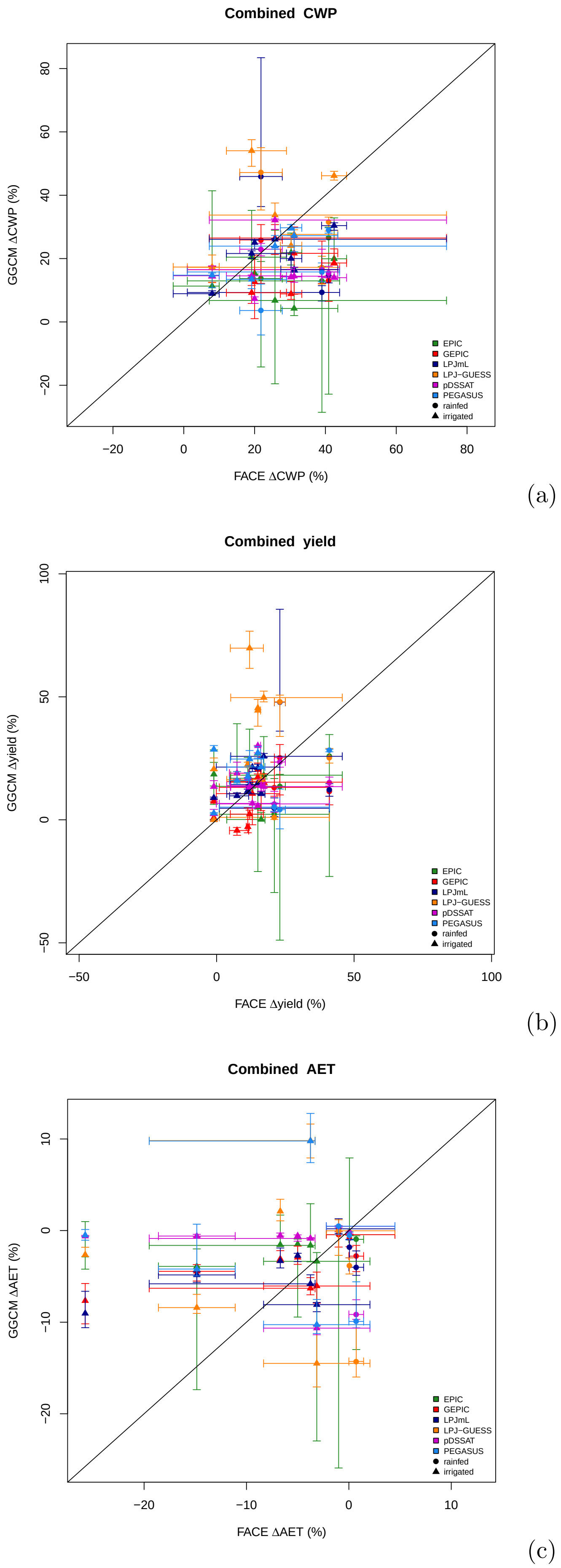

Figure S4: Scatter plots of GGCMs versus FACE measurements for CWP (a), yield (b) and AET (c). Results for both wet and dry experiments are shown. Circles and triangles represent median ΔCWP, Δyield and ΔAET under wet and dry conditions, respectively. Whiskers span the range of observations (horizontal) and simulations (vertical) per site and model.

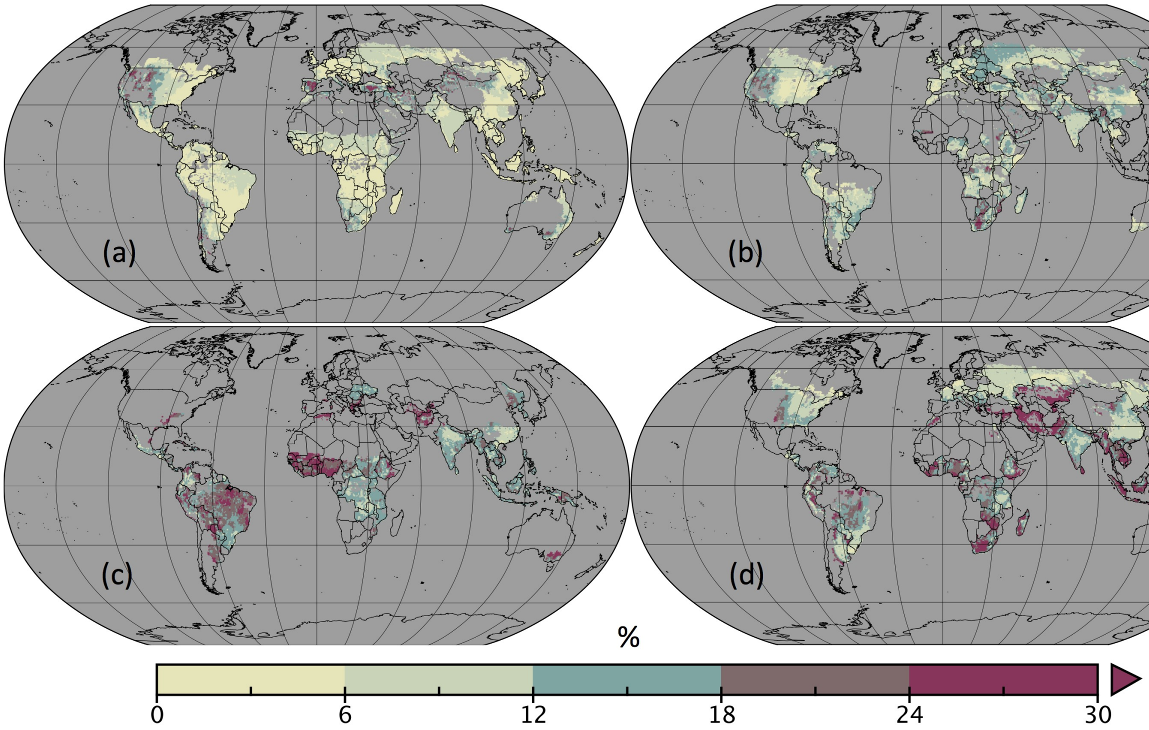

Figure S5: Median Absolute Deviation (MAD) from the median relative change between simulated $CWP\ w/\ CO_2$ and $w/o\ CO_2$ only in the model ensemble (inc. 6 GGCMs × 5 GCMs) by the 2050s under RCP 8.5. Rainfed simulations are shown for maize (a), wheat (b), rice (c) and soybean (d). Simulated areas are masked by current rainfed areas from the MIRCA dataset.

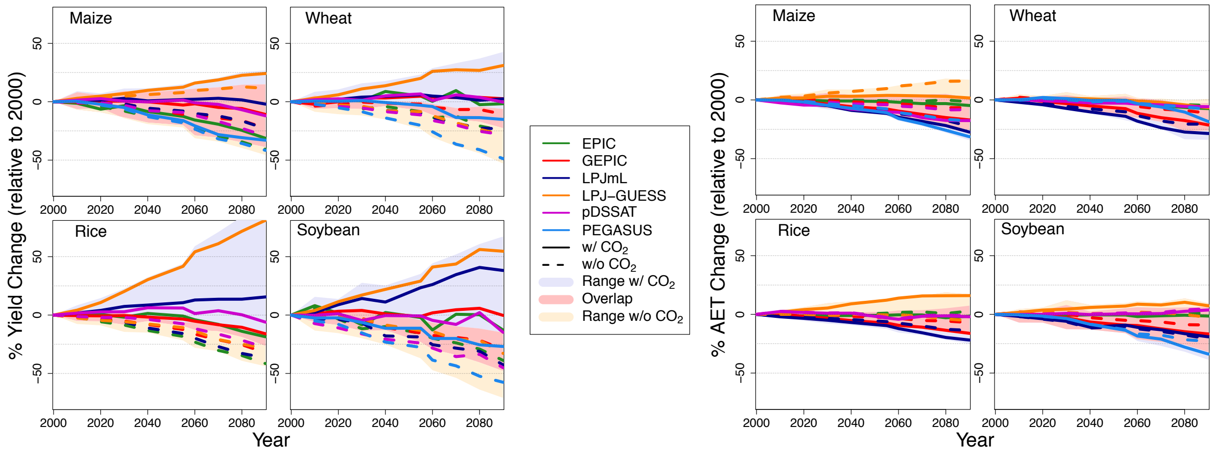

Figure S6: Global average yield (left) and AET (right) (%) relative to 2000 simulated under RCP 8.5 for each GGCM driven by five different GCMs. Solid lines show median yield under both climate change and CO_2 effects whereas dashed-lines show median yield under climate change effects only, i.e., with constant $[CO_2]$. Shaded areas show the range across the GGCM-GCM ensemble under $w/o\ CO_2$ (yellow) and $w/\ CO_2$ (blue), distinctively, and overlap between $w/o\ CO_2$ and $w/\ CO_2$ (red).

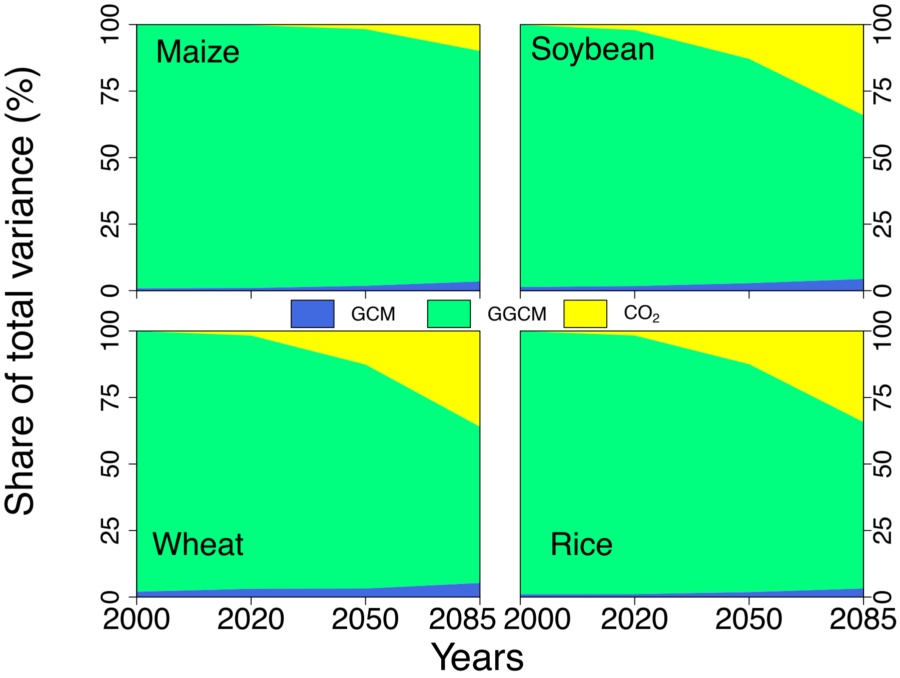

Figure S7: Share of the model ensemble total variance in simulating global CWP resulting from differences in (1) GCMs climate scenarios, (2) GGCMs response, and (3) CO_2 effects for maize, wheat, soybean and rice under RCP 8.5.

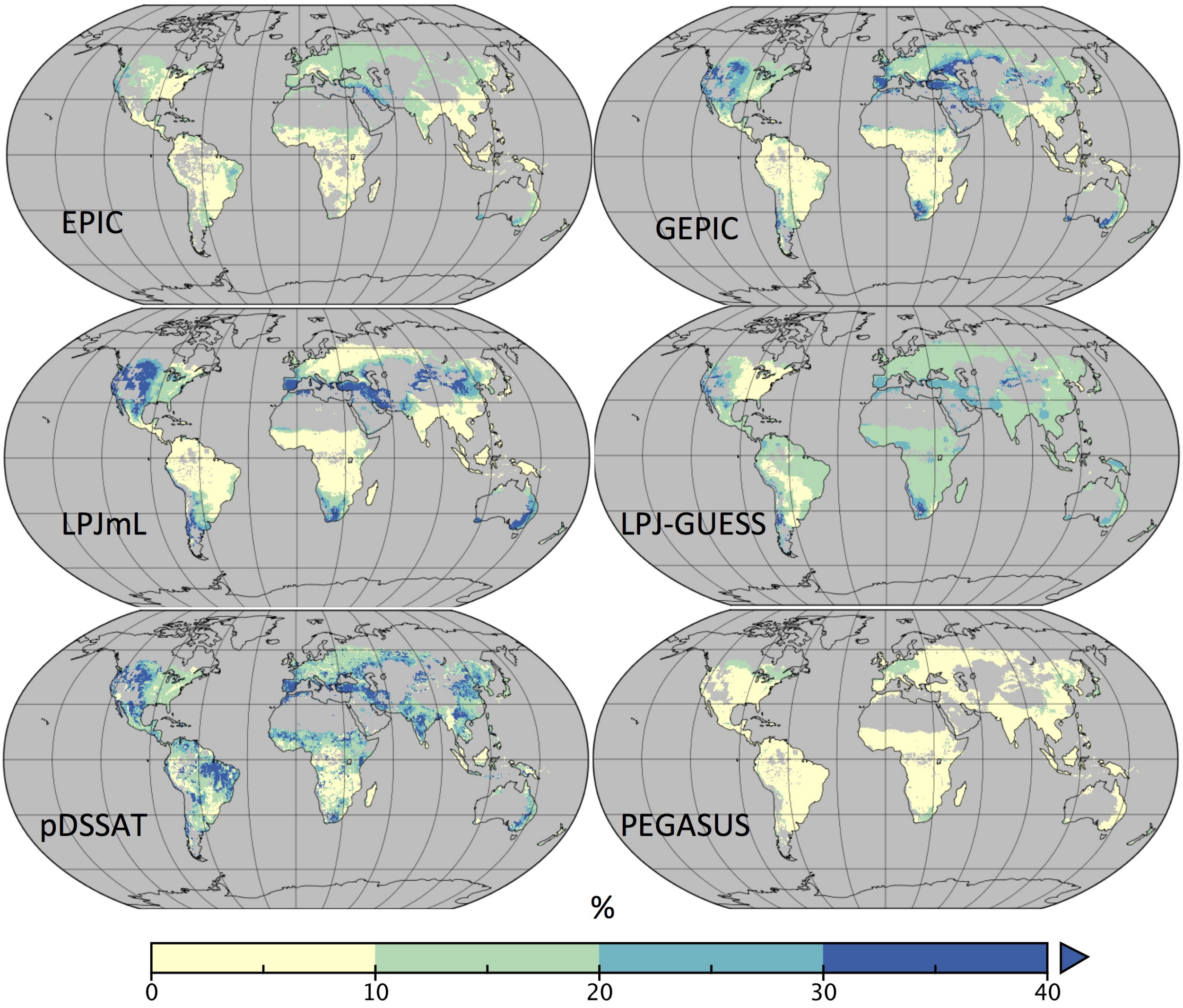

Figure S8: Maize: Map of median relative change between simulated CWP w/ CO_2 and w/o CO_2 only (%) by the 2050s under RCP 8.5 for each GGCM driven by 5 GCMs. Rainfed simulations are shown for maize. Simulated areas are masked by current rainfed areas from the MIRCA dataset.

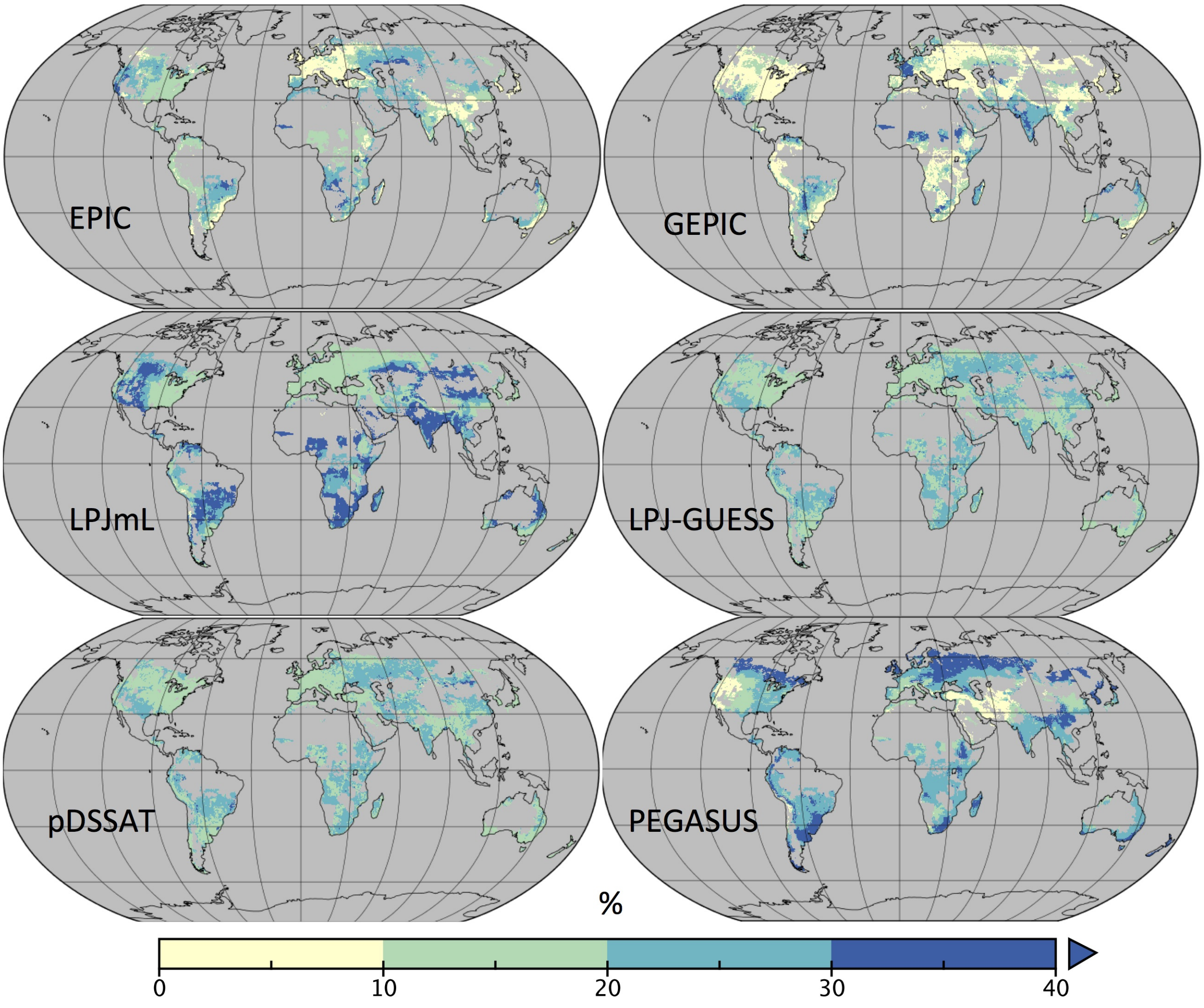

Figure S9: Same as Fig. S8 for wheat

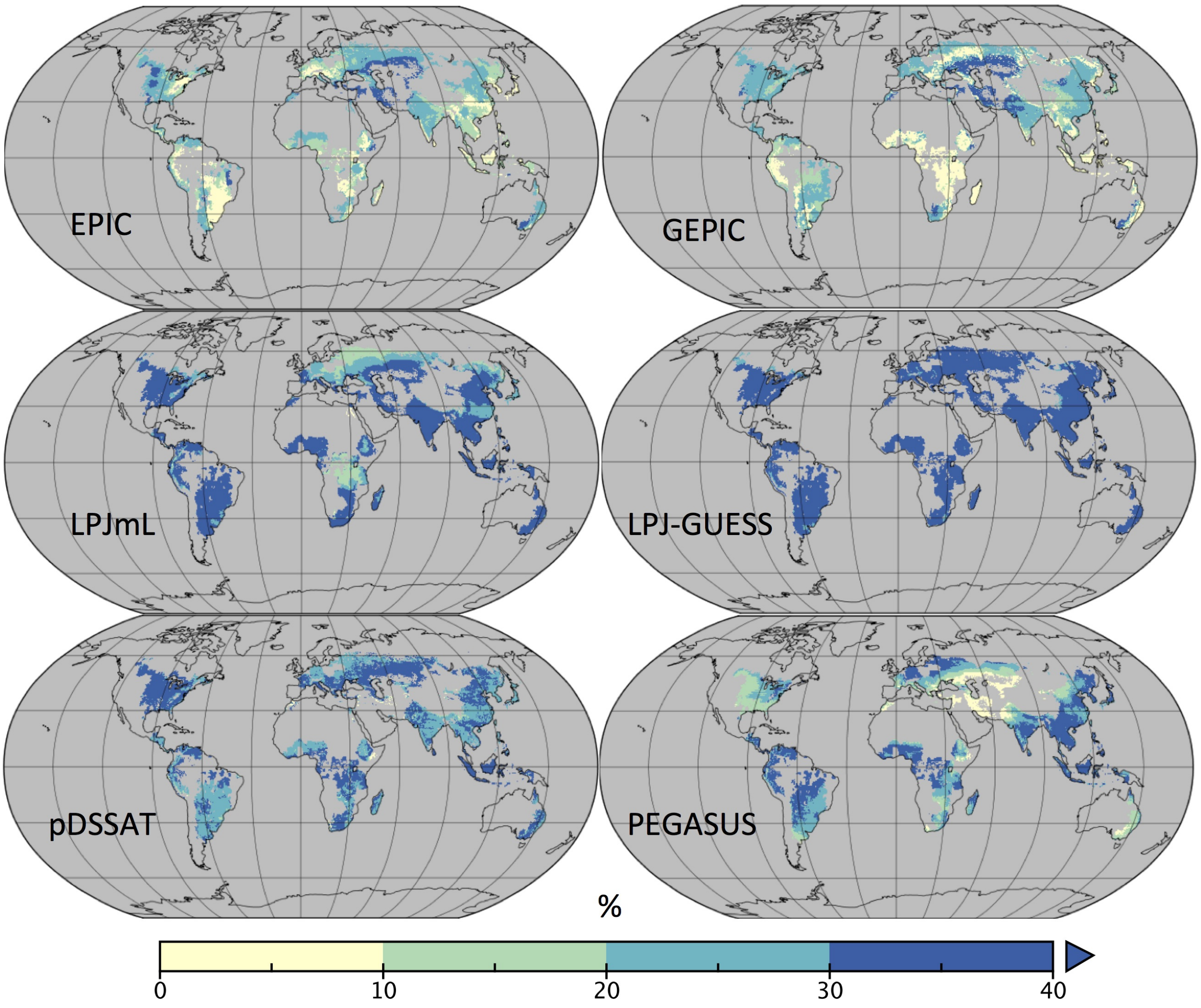

Figure S10: Same as Fig. S8 for soybean

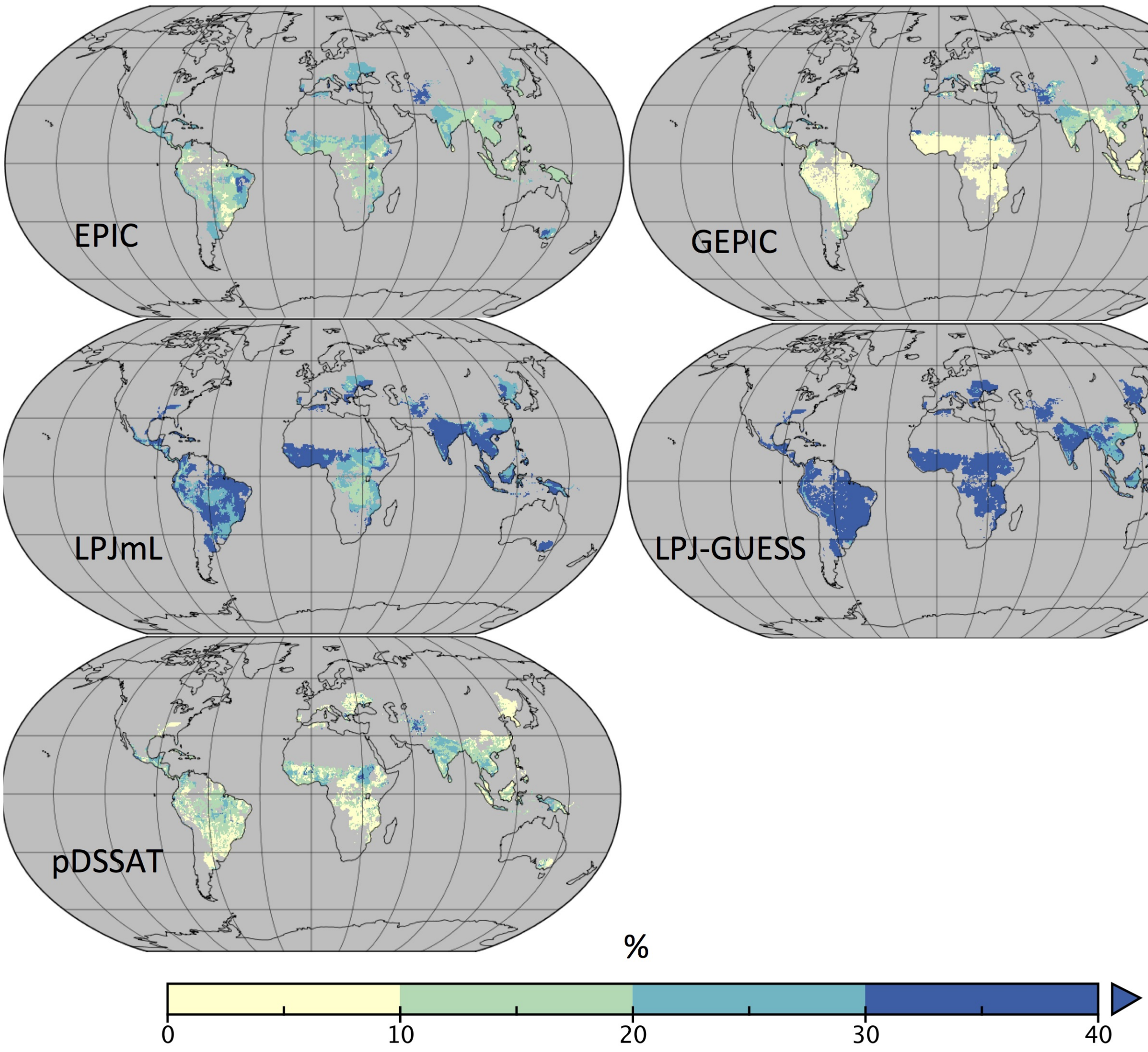

Figure S11: Same as Fig. S8 for rice. Note PEGASUS does not simulate rice.

References

Bernacchi, C. J., Kimball, B. A., Quarles, D. R., Long, S. P., and Ort, D. R. (2006). Decreases in stomatal conductance of soybean under open-air elevation of $[CO_2]$ are closely coupled with decreases in ecosystem evapotranspiration. *Plant Physiology*, 143(1):134–144.

Burkart, S., Manderscheid, R., Wittich, K. P., Löpmeier, F. J., and Weigel, H. J. (2011). Elevated CO_2 effects on canopy and soil water flux parameters measured using a large chamber in crops grown with free-air CO_2 enrichment. *Plant Biology*, 13(2):258–269.

Cai, C., Yin, X., He, S., Jiang, W., Si, C., Struik, P. C., Luo, W., Li, G., Xie, Y., Xiong, Y., and Pan, G. (2015). Responses of wheat and rice to factorial combinations of ambient and elevated CO2 and temperature in FACE experiments. *Global Change Biology*, pages n/a–n/a.

Christensen, J., Kumar, K. K., Aldrian, E., An, S.-I., Cavalcanti, I., de Castro, M., Dong, W., Goswami, P., Hall, A., Kanyanga, J., Kitoh, A., Kossin, J., Lau, N.-C., Renwick, J., Stephenson, D., Xie, S.-P., and Zhou, T. (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, chapter 14. Climate Phenomena and their Relevance for Future Regional Climate Change. Cambridge University Press.

Han, X., Hao, X., Lam, S. K., Wang, H., Li, Y., Wheeler, T. R., Ju, H., and Lin, E. (2015). Yield and nitrogen accumulation and partitioning in winter wheat under elevated CO2: A 3-year free-air CO2 enrichment experiment. *Agriculture, Ecosystems & Environment*, 209:132–137.

Hunsaker, D. J., Kimball, B. A., Pinter, P. J., LaMorte, R. L., and Wall, G. W. (1996). Carbon dioxide enrichment and irrigation effects on wheat evapotranspiration and water use efficiency. *Transactions of the ASAE*, 39(4):1345–1355.

Hunsaker, D. J., Kimball, B. A., Pinter, Jr., P. J., Wall, G. W., LaMorte, R. L., Adamsen, F. J., Leavitt, S. W., Thompson, T. L., Matthias, A. D., and Brooks, T. J. (2000). CO2 enrichment and soil nitrogen effects on wheat evapotranspiration and water use efficiency. *Agricultural and Forest Meteorology*, 104(2):85–105.

Kim, H.-Y., Lieffering, M., Kobayashi, K., Okada, M., Mitchell, M. W., and Gumpertz, M. (2003). Effects of free-air CO_2 enrichment and nitrogen supply on the yield of temperate paddy rice crops. *Field Crops Research.*

Kimball, B. A., LaMorte, R. L., Pinter, Jr., P. J., Wall, G. W., Hunsaker, D. J., Adamsen, F. J., Leavitt, S. W., Thompson, T. L., Matthias, A. D., and Brooks, T. J. (1999). Free-air CO_2 enrichment and soil nitrogen effects on energy balance and evapotranspiration of wheat. *Water Resources Research*, 35(4):1179–1190.

Liu, H., Yang, L., Wang, Y., Huang, J., Zhu, J., Yunxia, W., Dong, G., and Liu, G. (2008). Yield formation of CO2-enriched hybrid rice cultivar Shanyou 63 under fully open-air field conditions. *Field Crops Research*, 108(1):93–100.

Manderscheid, R., Erbs, M., and Weigel, H.-J. (2012). Interactive effects of free-air CO_2 enrichment and drought stress on maize growth. *European Journal of Agronomy.*

Morgan, P. B., Bollero, G. A., Nelson, R. L., Dohleman, F. G., and Long, S. P. (2005). Smaller than predicted increase in aboveground net primary production and yield of field-grown soybean under fully open-air [CO2] elevation. *Global Change Biology*, 11(10):1856–1865.

O'Leary, G. J., Christy, B., Nuttall, J., Huth, N., Cammarano, D., Stöckle, C., Basso, B., Shcherbak, I., Fitzgerald, G., Luo, Q., Farre Codina, I., Palta, J., and Asseng, S. (2015). Response of wheat growth, grain yield and water use to elevated CO2 under a Free-Air CO2 Enrichment (FACE) experiment and modelling in a semi-arid environment. *Global Change Biology*, 21(7):2670–2686.

Shimono, H., Nakamura, H., Hasegawa, T., and Okada, M. (2013). Lower responsiveness of canopy evapotranspiration rate than of leaf stomatal conductance to open-air CO_2 elevation in rice. *Global Change Biology*, 19(8):2444–2453.

Shimono, H., Okada, M., Yamakawa, Y., Nakamura, H., Kobayashi, K., and Hasegawa, T. (2008). Rice yield enhancement by elevated CO2 is reduced in cool weather. *Global Change Biology*, 14(2):276–284.

Weigel, H.-J. and Manderscheid, R. (2012). Crop growth responses to free air CO2 enrichment and nitrogen fertilization: Rotating barley, ryegrass, sugar beet and wheat. *European Journal of Agronomy*, 43:97–107.

Yang, L., Huang, J., Yang, H., Zhu, J., Liu, H., Dong, G., Liu, G., Han, Y., and Wang, Y. (2006). The impact of free-air CO2 enrichment (FACE) and N supply on yield formation of rice crops with large panicle. *Field Crops Research*, 98(2-3):141–150.

Yang, L., Liu, H., Wang, Y., Zhu, J., Huang, J., Liu, G., Dong, G., and Wang, Y. (2009). Yield formation of CO2-enriched inter-subspecific hybrid rice cultivar Liangyoupeijiu under fully open-air field condition in a warm sub-tropical climate. *Agriculture, Ecosystems & Environment*, 129(1-3):193–200.

Zhang, G., Sakai, H., Tokida, T., Usui, Y., Zhu, C., Nakamura, H., Yoshimoto, M., Fukuoka, M., Kobayashi, K., and Hasegawa, T. (2013). The effects of free-air CO2 enrichment (FACE) on carbon and nitrogen accumulation in grains of rice (Oryza sativa L.). *Journal of Experimental Botany*, 64(11):3179–3188.

Zhu, C., Xu, X., Wang, D., Zhu, J., and Liu, G. (2015). An indica rice genotype showed a similar yield enhancement to that of hybrid rice under free air carbon dioxide enrichment. *Scientific Reports*, 5:12719.