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Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison

Supplementary Appendix

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Table S1. List of global GGCMs, participants, and references:

Model	Version	References for model description and applications	Institution	Contact person / Web address
EPIC	EPIC0810	1,2	BOKU; University of Natural Resources and Life Sciences, Vienna	Erwin Schmid erwin.schmid@boku.ac.at
GEPIC	EAWAG	3,4	EAWAG (Swiss Federal Institute of Aquatic Science and Technology)	Christian Folberth/Hong Yang Christian.folberth@eawag.ch Hong.yang@eawag.ch
GAEZ in IMAGE	2.4	5,6	Netherland Environmental Assessment Agency (PBL)	Elke Stehfest/Kathleen Neumann Elke.stehfest@pbl.nl Kathleen.Neumann@pbl.nl
LPJmL	-	7,8,9,10	Potsdam Institute for Climate Impact Research	Christoph Müller Christoph.Mueller@pik-potsdam.de www.pik-potsdam.de/lpj
LPJ-GUESS	2.1 with crop module	7,11,12	Lund University, department for Physical Geography and Ecosystem Scince, IMK-IFU, Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany	Stefan Olin/Thomas Pugh Stefan.Olin@nateko.lu.se thomas.pugh@imk.fzk.de
pDSSAT	pDSSAT1.0 (DSSAT4.0)	13,14*	University of Chicago Computation Institute	Joshua Elliott, jelliott@ci.uchicago.edu
PEGASUS	V. 1.1	15	Tyndall Centre University of East Anglia, UK / McGill University, Canada	Delphine Deryng d.deryng@uea.ac.uk

*DSSAT cropping system model includes CERES maize, rice, and wheat and CROPGRO soybean.

Table S2: Summary of Key characteristics and differences in GGCMs.

	EPIC	**GEPIC**	**GAEZ-IMAGE**	**LPJ-GUESS**	**LPJmL**	**pDSSAT**	**PEGASUS**
Type[1]	Site-based	Site-based	GAEZ	Ecosystem	Ecosystem	Site-based	Ecosystem
CO_2 effects[2]	RUE, TE	RUE, TE	RUE	LF, SC	LF, SC	RUE (for wheat, rice, maize) and LF (for soybean)	RUE, TE
Stresses[3]	W, T, H, A, N, P, BD, AL	W, T, H, A, N, P, BD, AL	W, T	W, T	W, T	W, T, H, A, N	W, T, H, N, P, K
Fertilizer application[4]	automatic N input (max 200 kg Ha-1 yr-1) PK (national stat. IFA) dynamic application	NP (national stat: FertiSTAT), dynamic application	No nutrient limitation	na	na	SPAM, dynamic application	NPK (national stat. IFA), annual application
Calibration[5] **Parameters**	Site-specific (EPIC 0810) Na	Site-specific and global F HI_{pot} (for maize and rice)	Na Na	Uncalibrated na	Global LAI_{max} HI α_a	Site-specific (DSSAT) Na	Global β
Outputs	Actual yield & yield gap	Actual yield	Potential yield	Potential yield	Actual yield	Actual yield	Actual yield

Notes for abbreviations (na = not applicable)**:**

(1) site-base crop model; GAEZ: Global agro-ecological zones; ecosystem: global ecosystem model

(2) Elevated CO_2 effects: LF: Leaf-level photosynthesis (via rubisco or quantum-efficiency and leaf-photosynthesis saturation; RUE: Radiation use efficiency; TE: Transpiration efficiency; SC: stomatal conductance

(3) W: water stress; T: temperature stress; H: specific-heat stress; A: oxygen stress; N: nitrogen stress; P: phosphorus stress; K: potassium stress; BD: bulk density; AL: aluminum stress (based on pH and base saturation)

(4) Fertilizer application, timing of application; NPK annual application of total NPK (nutrient-stress factor); source of fertilizer application data; timing: annual or dynamic

(5) F: fertilizer application rate; HI_{pot}: Potential harvest index; LAI_{max}: maximum LAI under unstressed conditions; HI: harvest index; α_a: factor for scaling leaf-level photosynthesis to stand level; β: radiation-use efficiency factor.

Table S3. Documenting biophysical processes:

Model	Leaf area developmen[1]	Light interception[2]	Light utilisation[3]	Yield formation[4]	Stresses involved[5]	Type of heat stress[6]	Crop phenology[7]	Type of water stress[8]	Evapo-transpiration[9]	Soil water dynamic[10]	Root distribution over depth[11]	Soil CN model[12]	CO_2 effects[13]
EPIC	D	S	RUE	HI_{ws} Prt B	W T H A N P BD AL	V	T(HU) V O	E	PM	10	LIN W	C N B(1) P(6)	RUE TE
GEPIC	D	S	RUE	HI_{ws} Prt B	W T H A N P BD AL	V	T(HU) V O	E	PM	5	LIN W	C N B(1) P(6)	RUE TE
IMAGE	D	S	RUE	HI	W T BD	NA	T	E	PT	1	W	NA	RUE
LPJ-GUESS	D	S	P-R	HI_{ws}	W T	NA	T V	S	PT	2	LIN	NA	LF, SC
LPJmL	PS	S	P-R	HI_{ws}	W T	NA	T V	S	PT	5	EXP	NA	LF, SC
pDSSAT	D	S ; Soy :D	RUE; soy: P-R	Gn	W T H A N	V R F	T V DL O	E	PT	4	EXP	C N P(3)	RUE, TE, soy: LF, TE
PEGASUS	D	S	RUE	Prt	W T H N P K	V F	T(HU)	E	PT	3	LIN W	NA	RUE TE

Notes for abbreviations (NA where not applicable)**:**

(1) D: Dynamic simulation based on development and growth processes; PS: prescribed shape of LAI curve as function of phenology, modified by water stress & low productivity

(2) S: Simple approach: D: Detailed approach

(3) RUE: Simple (descriptive) radiation use efficiency approach; P-R: Detailed (explanatory) gross photosynthesis – respiration (for more details, see 16)

(4) Yield formation depending on: HI: fixed harvest – index; B: total (above – ground) biomass; Gn: number of grains and grain growth rate; Prt: partitioning during reproductive stages; HI_{ws}: HI modified by water stress

(5) W: water stress; T: temperature stress; H: specific-heat stress; A: oxygen stress; N: nitrogen stress; P: phosphorus stress; K: potassium stress; BD: bulk density; AL: aluminum stress (based on pH and base saturation)

(6) V: vegetative (source); R: reproductive organ (sink); F: number of grain (pod) set during the flowering period

(7) Crop phenology is a function of: T: temperature; DL: photoperiod (day length); O: other water/nutrient stress effects considered; V: vernalization; HU: Heat unit index

(8) E: ratio of supply to demand of water; S: soil available water in root zone

(9) PM: Penman – Monteith; PT: Priestley –Taylor

(10) number of soil layers

(11) LIN: linear; EXP: exponential; W: actuals water depends on water availability in each soil layer

(12) C model; N model; P(x): x number of organic matter pools; B(x): x number of microbial biomass pools

(13) Elevated CO_2 effects: LF: Leaf-level photosynthesis (via rubisco or quantum-efficiency and leaf-photosynthesis saturation; RUE: Radiation use efficiency; TE: Transpiration efficiency; SC: stomatal conductance

Table S4. Documenting model inputs and agricultural management practices:

Model	**Spatial scale**	**Temp-oral scale**[1]	**Climate input variables**[2]	**Soil input data**[3]	**Spin Up**[4]	**Planting date decision**[5]	**Crop cultivars**[6]	**Irri-gation rules**[7,8]	**Fertilizer application**[9]	**Crop residue**[10]	**CO_2**[11]
EPIC	0.5° lon x 0.5° lat	D, H,	Tmn, Tmx, P, Rad, RH, WS	ISRIC-WISE (17) ROSETTA (18) AWC (19) ALBEDO (20) HYD (21)	Soil OM, C, NH_3, NO_3, H_2O, P(1)	S (fraction of PHU), fixed planting window	GDD - fixed	90/100/500/50/20[8] maximum applied irrigation: 500 mm yr^{-1}	automatic N input (max 200 kg Ha^{-1} yr^{-1}) PK (national stat. IFA) dynamic application	No, can be simulated	380 ppm (2005)
GEPIC	0.5° lon x 0.5° lat	D	Tmn, Tmx, P, Rad, RH, WS	ISRIC-WISE (17)	Soil OM, C, NH_3, NO_3, H_2O, P, CR (20)	S (fraction of PHU), clim. adapt	GDD, 2 cultivars for mai - fixed	90/100/2000/1000/0.01[8]	NP (national stat. FertiSTAT), dynamic application	Yes, Crop-specific	364 ppm (2000)
IMAGE	0.5° lon x 0.5° lat	M, WG	Ta,P	Soil reduction factor (22) based on FAO soil map (23)	CR(210)	clim. Adapt (implicit planting date)	GDD + clim. adapt	NA	NA	Yes, does not affect yield	370 ppm (2000)
LPJ-GUESS	0.5° lon x 0.5° lat	D	Ta, P, cld (or Rad)	HWSD (24), STC HYD (25) THM (26)	H_2O (30)	S (9), fixed planting window	GDD+V (whe, sunfl, rapes); BT (mai); static (others) + clim. adap	200/90/100/100[7]	NA	Yes, does not affect yield	379 ppm (2005)
LPJmL	0.5° lon x 0.5° lat	D	Ta, P, cld (or Rad)	HWSD (24), STC HYD (25) THM (26)	H_2O (200)	S (9), fixed planting day after 1951	GDD+V (whe, sunfl, rapes); BT (mai); static (others) - fixed	300/90/100/varies[7]	NA	Yes, does not affect yield	370 ppm (2000)
pDSSAT	0.5° lon x 0.5° lat	D	Tmn, Tmx, P, Rad	HWSD (24)	Soil OM, C, NH_3, NO_3, H_2O (1)	S (27), fixed planting window	GDD and/or latitude, 2-3 for each cell - fixed	40/80/100/75[7] ric: 30/50/100/100[7]	SPAM (28), dynamic application	Yes, does not affect yield	330 ppm (1975)
PEGASUS	0.5° lon x 0.5° lat	D	Ta, Tmn, Tmx, P, cld (or sun)	AWC (ISRIC-WISE, 17)	H_2O (4)	S (15), clim. adapt	GDD + clim. adapt	40/90/100/100[7]	NPK (national stat. IFA), annual application	NA	369 ppm (2000)

Notes for abbreviations (NA where not applicable)**:**

(1) D: daily time-step; M: monthly time-step; H: hourly time-step; WG: use monthly climate data interpolated to daily using a weather-generator

(2) Ta: average temperature, Tmn: minimum temperature, Tmx: maximum temperature, cld: percentage of cloud cover, sun: fraction of sunshine hours; RH: relative humidity; WS: wind speed

(3) Source of soil property inputs (e.g., source of basic soil properties), plus method for manipulation to derive parameters required by the model); AWC: Available Water Capacity; HYD: hydraulic soil parameters; THM: thermal parameters; HWSD: Harmonized world soil database (24); STC: soil texture classification based on the USDA soil texture classification (http://edis.ifas.ufl.edu/ss169); ISRIC-WISE (17); ROSETTA (18)

(4) Number years for Spin up (x); OM: organic matter, C: carbon; NH_3: ammonia; NO_3: nitrate; H2O: soil water; P: phosphorus; CR: crop residus

(5) S: Simulate planting dates according to climatic conditions; F: fixed planting dates; source of planting date data if applicable; PHU: potential heat unit; fixed planting window (i.e., does not allow for adaptation to climate change); clim. adapt: dynamic planting window (adaptation to climate change)

(6) GDD: Simulate crop Growing Degree Days (GDDs) requirement according to estimated annual GDDs from daily temperature; Number of cultivars; GDD+V GDD requirements and vernalization requirements computed based on past climate experience; BT base temperature computed based on past climate; fixed: static GDD requirement (no adaptation); clim. adapt: dynamic GDD requirement (adaptation to climate change)
(7) Irrigation rules: IMDEP(cm): depth of soil moisture measured; ITHRL(%): critical lower soil moisture threshold to trigger irrigation event; ITHRU(%): upper soil moisture threshold to stop irrigation; IREFF(%): irrigation application efficiency
(8) Irrigation rules: EPIC and GEPIC models: BIR(%): water stress in crop to trigger automatic irrigation; EFI(%): irrigation efficiency - runoff from irrigation water; VIMX(mm): maximum of annual irrigation volume; ARMX(mm): maximum of single irrigation volume allowed; ARMN(mm): minimum of single irrigation volume allowed
(9) Fertiliser application, timing of application; NPK annual application of total NPK (nutrient-stress factor); source of fertiliser application data; timing: annual or dynamic
(10) Remove residue or not (Yes/No)
(11) CO_2 concentration baseline for “no CO_2” simulations (+ corresponding year)

Table S5: Documenting method for model calibration and validation (NA where Not Applicable):

Model	Model origin[1]	Calibration method	Parameters for calibration[2]	Output variable and dataset for calibration[3]	Spatial scale of calibration	Temporal scale of calibration	Method for model evaluation[4]
EPIC	Site-based	Site-specific (EPIC 0810)	NA	Yield (FE & FAO)	Field scale & National	Various	NA
GEPIC	Site-based	Site-specific (EPIC 0810) & Global*	F HI_{pot} (mai, ric)	Yield (FE & FAO)	National	Average for 1997-2003	R^2
IMAGE	GAEZ	NA	NA	Potential Yield	National	Average 1970-2005	NA
LPJ-GUESS	ecosystem	Uncalibrated	NA	NA	NA	NA	NA
LPJmL	ecosystem	Global	LAI_{max} HI α_a	Yield (FAO)	National	Average for 1998-2003	Wilmott
pDSSAT	Site-based	Site-specific (DSSAT)	NA	Yield (FE)	Field scale	Various	NA
PEGASUS	ecosystem	Global	β	Yield (M3)	Gridcell level (0.5ºlon x0.5ºlat resolution)	Average for 1997-2004	Wilmott

Notes for abbreviations:
(1) site-base crop model; GAEZ: Global agro-ecological zones; ecosystem: global ecosystem model
(2) F: fertiliser application rate; HI_{pot}: Potential harvest index; LAI_{max}: maximum LAI under unstressed conditions; HI: harvest index; α_a: factor for scaling leaf-level photosynthesis to stand level; β: radiation-use efficiency factor
(3) FE: field experiments; FAO: FAOSTAT national yield statistic; M3: gridded dataset of crop specific yields and harvested areas for the year 2000 (29)
(4) Willmott: maximise Wilmott index of agreement (d) and RMSEu>RMSEs (RMSE: root-mean-square error; RMSEu: unsystematic RMSE; RMSEs: systematic RMSE) (30)
* GEPIC: Default parameters coming with the field scale model EPIC0810 are mostly used. Potential HI has been adjusted for maize cultivars and rice based on literature (field trials). Fertilizer application rates have been modified for few countries that report very high yields and low fertilizer use, whereas most of these countries are known for their intensive use of manure.

Table S6: List of simulation experiments and GGCMs outputs

GGCMs	GCMs-RCPs-CO_2	CROP	OUTPUT[1]
EPIC	HADGEM2-ES + 4RCPs-CO_2 + 4RCPs-noCO_2 IPSL-CM5A-LR + 4RCPs-CO_2 + RCP8.5-noCO_2 MIROC-ESM-CHEM + 4RCPs-CO_2 + RCP8.5-noCO_2 GFDL-ESM2M + 4RCPs-CO_2 + RCP8.5-noCO_2 NorESM1-M + 4RCPs-CO_2 + RCP8.5-noCO_2	maize, wheat, soybean, rice, barley, managed grass, millet, rapeseed, sorghum, sugarcane, drybean, cassava, cotton, sunflower, groundnut	YIELD, PIRRWW, AET
GEPIC[2]	HADGEM2-ES + 4RCPs-CO_2 + 4RCPs-noCO_2 IPSL-CM5A-LR + 4RCPs-CO_2 MIROC-ESM-CHEM + 4RCPs-CO_2 GFDL-ESM2M + 4RCPs-CO_2 NorESM1-M + 4RCPs-CO_2	maize, wheat, soybean, rice	YIELD, PIRRWW, AET
IMAGE	HADGEM2-ES + 4RCPs-CO_2 + 4RCPs-noCO_2 IPSL-CM5A-LR + 4RCPs-CO_2 MIROC-ESM-CHEM + 4RCPs-CO_2 GFDL-ESM2M + 4RCPs-CO_2 NorESM1-M + 4RCPs-CO_2	maize, wheat, soybean, rice	YIELD
LPJ-GUESS	HADGEM2-ES + 4RCPs-CO_2 + 4RCPs-noCO_2 IPSL-CM5A-LR + 4RCPs-CO_2 MIROC-ESM-CHEM + 4RCPs-CO_2 GFDL-ESM2M + 4RCPs-CO_2 NorESM1-M + 4RCPs-CO_2	maize, wheat, soybean, rice	YIELD, PIRRWW, AET
LPJmL	HADGEM2-ES + 4RCPs-CO_2 + 4RCPs-noCO_2 IPSL-CM5A-LR + 4RCPs-CO_2 + 4RCPs-noCO_2 MIROC-ESM-CHEM + 4RCPs-CO_2 + 4RCPs-noCO_2 GFDL-ESM2M + 4RCPs-CO_2 + 4RCPs-noCO_2 NorESM1-M + 4RCPs-CO_2 + 4RCPs-noCO_2	maize, wheat, soybean, rice, millet, cassava, sugar beet, field pea, rapeseed, sunflower, groundnut, sugarcane	YIELD, PIRRWW, AET, PLANT-DAY, MATY-DAY, BIOM, , GSPRCP, GSRSDS, SUMT
pDSSAT	HADGEM2-ES + 4RCPs-CO_2 + 4RCPs-noCO_2 IPSL-CM5A-LR + 4RCPs-CO_2 + 4RCPs-noCO_2 MIROC-ESM-CHEM + 4RCPs-CO_2 + 4RCPs-noCO_2 GFDL-ESM2M + 4RCPs-CO_2 + 4RCPs-noCO_2 NorESM1-M + 4RCPs-CO_2 + 4RCPs-noCO_2	maize, wheat, soybean, rice	YIELD, PIRRWW, AET, GSPRCP
PEGASUS[3]	HADGEM2-ES + 4RCPs-CO_2 + 4RCPs-noCO_2 IPSL-CM5A-LR + 4RCPs-CO_2 + RCP8.5-noCO_2 MIROC-ESM-CHEM + 4RCPs-CO_2 + RCP8.5-noCO_2 GFDL-ESM2M + 4RCPs-CO_2 + RCP8.5-noCO_2 NorESM1-M + 4RCPs-CO_2 + RCP8.5-noCO_2	maize, wheat, soybean	YIELD, PIRRWW, AET, PLANT-DAY, ANTH-DAY, MATY-DAY, INITR, ONITR, BIOM, LEACH, GSPRCP, GSRSDS, SUMT

Outputs description:

(1) YIELD (ton ha^{-1} yr^{-1}): dry matter; PIRRWW (mm yr^{-1}): potential irrigation water withdrawal; AET (mm yr^{-1}): actual growing season evapotranspiration; PLANT_DAY (julian day): planting date; ANTH-DAY (day from planting): date of anthesis; MATY-DAY (day from planting): maturity date; INITR (ton ha^{-1} yr^{-1}): inorganic nitrogen application rate; ONITR (ton ha^{-1} yr^{-1}): organic nitrogen application rate; BIOM (ton ha^{-1} yr^{-1}): total above ground biomass yield; LEACH (ton ha^{-1} yr^{-1}): nitrogen leached; GSPRCP (mm yr^{-1}): growing season precipitation; GSRSDS (W m^{-2} yr^{-1}): growing season incoming solar radiation; SUMT (C^o-day yr^{-1}): sum of daily mean temperature over growing season;

(2) GEPIC: All GEPIC outputs for HadGEM2-ES have been shifted by one year in the period 2005-2030. Note as of January 21st, 2013, data have been updated on the server.

(3) PEGASUS: Outputs for NorESM1-M+RCP4.5 wheat are not available

S1. Model Processes

The geneaology of GGCMs included in this study is presented in **Figure S1**. Key characteristics of each GGCM are provided in **Tables S1-S6**.

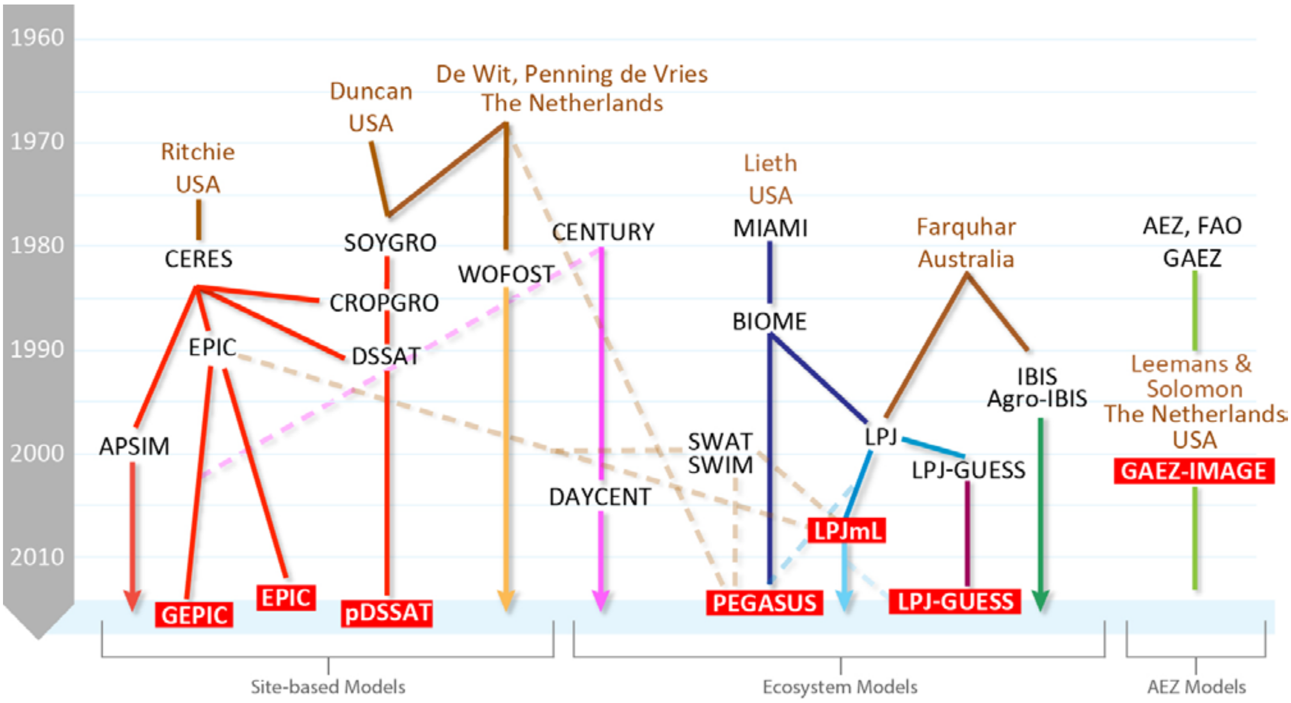

Figure S1: Crop model genealogy for site-based, ecosystem, and AEZ models. The models examined in this study are marked in red boxes.

S1.1. Differences between similar model versions

LPJ-GUESS simulates potential yield, while LPJmL simulates actual yields, and their main difference is the allocation scheme to the different crop organs, in which the leaf area index (LAI) development is either a function of phenology and management intensity (LPJmL) or a direct feedback of daily net primary production and leaf area index (LPJ-GUESS). GEPIC and EPIC both use an automatic N fertilization and irrigation schedule constrained by upper limits (200 N kg/ha/a and 500 mm/a, respectively in EPIC; FertiSTAT values and 2000 mm/a, respectively, in GEPIC). In addition, GEPIC simulations were run for each decade separately with a 20-year spin-up in order to equilibrate soil processes while preventing total soil nutrient depletion (31).

S1.2 CO_2 effects

GGCMs differ in whether and how they include the potentially beneficial effects on crops of elevated [CO_2] from greenhouse gas emissions and related carbon cycle feedbacks. Effects on crop growth are simulated in LPJmL, LPJ-GUESS, and DSSAT-Soybean with detailed leaf-level biochemistry photosynthesis (via rubisco or quantum efficiency, QE, and light-saturated photosynthesis, Amax; 32) and in PEGASUS, EPIC, GEPIC, and CERES maize, wheat, and rice models in DSSAT through increased radiation use efficiency (RUE). Some models include high [CO_2] effects on canopy conductance (LPJmL, LPJ-GUESS). The site-based crop models (EPIC, GEPIC and pDSSAT) include interactions with nitrogen in the CO_2 responses, reducing positive effects under low nitrogen conditions. Furthermore, slightly different constant [CO_2] values, ranging from 330 to 380 ppm, are used by each model in experiments where [CO_2] was held constant although these differences probably do not play a large role in the results. All the GGCMs used daily climate inputs, which limits their ability to explicitly resolve the diurnal cycles of carbon fluxes as do some carbon and ecosystem models (some processes in EPIC and pDSSAT are simulated on an hourly timestep). Deryng et al. (33) present a more detailed comparison of the seven GGCMs with respect to the simulation of CO_2 effects.

S1.3 Temperature and heat effects

The characteristics of GGCMs' sensitivity to temperature changes and acute heat stress could drive a substantially different response to both mean climate change and the interacting interannual and intraseasonal variability. In all the GGCMs, crop phenology is a function of temperature, via accumulated growing degree days. In some GGCMs, phenology also responds to photoperiod and water and nutrient stresses. Some models include vernalization of winter varieties, and some but not all the GGCMs respond to specific heat stress, such as heat stress at anthesis and the effects of high temperature on grain growth during the crop's reproductive phase (33).

S1.4 Evapotranspiration

Differences in the procedure used to simulate evapotranspiration could substantially affect the regions and severity of water stress impacts under future climate change. Different GGCMs utilize Penman (Penman, 1948; available in EPIC and GEPIC), Penman-Monteith (Monteith, 1965; available in EPIC, GEPIC, and pDSSAT), Priestley –Taylor (1972; available in EPIC, GEPIC, and pDSSAT, and used in GAEZ-IMAGE, LPJmL, and PEGASUS), Hargreaves (Hargreaves and Samani, 1985; available in EPIC and GEPIC), and Baier-Robertson (Baier and Robertson, 1965; available in EPIC and GEPIC) methods to simulate evapotranspiration. For this study, EPIC used Penman-Monteith for potential evaporation. EPIC, GEPIC, and pDSSAT utilize crop-specific coefficients for calculation of actual evapotranspiration.

S1.5 Pests

EPIC includes a pest damage function, which was not activated in this analysis. However, many of these stresses do not apply to those models that simulate potential rather than actual yields (GAEZ-IMAGE and LPJ-GUESS).

S2. Model Configuration

S2.1 Soil properties

Sources of soil properties and methods for deriving GGCM inputs, such as available water capacity, include the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012), the USDA soil texture classification (http://edis.ifas.ufl.edu/ss169), ISRIC-WISE (Batjes, 2006), and ROSETTA (Shaap et Bouten,1996). Hydraulic and thermal soil parameters are included in some GGCMs. EPIC simulates soil degradation processes and runs each 30-year time slice independently rather than simulating a continuous time series.

S2.2 Crops

While some of the models include a wide range of crops and crop types, all the GGCMs simulate wheat, maize, and soybean, and all but PEGASUS simulate rice. Results presented here focus on those four crops, which are the top four global agricultural food commodities

S2.3 Land use and agricultural systems

All the models use a 0.5º grid, but there are differences in the grid cells simulated to represent agricultural land. While some models simulated all land areas, others simulated only potential suitable cropland area according to evolving climatic conditions and others utilized historical harvested areas in the year 2000 according to various data sources (e.g., the Spatial Production Allocation Model, SPAM; You et al., 2000).

There are key similarities and differences in GGCM inputs and management practices that may affect both the specific farming systems represented and their initial yield patterns even before they respond to projected climate changes (See **Tables S1-S5** above). The MIRCA2000 land use database (Portmann et al., 2010) is used for all models to identify the location of irrigated and non-irrigated areas.

There are differences in handling the fraction of grid-cell area covered by the crops and row spacing/planting density within the cropping areas. Some (but not all) models have mixed cropland, rotations, and multiple growing seasons (e.g., for aus, aman, and boro rice in Bangladesh).

S2.4 Planting date

Models differed in how planting and harvesting dates were handled in the intercomparison. All models simulated exact planting dates according to climatic conditions, but some allowed for dynamic planting windows (PEGASUS, GEPIC, and IMAGE), while others utilized fixed planting windows to historical values based on literature (EPIC based on [[citation needed]]; pDSSAT based on Sacks et al. 2010; LPJ-GUESS and LPJ-mL based on Waha et al., 2012). As an example of determining planting dates, the EPIC crop model that underlies the EPIC GGCM and GEPIC uses automatic adjustments of planting and harvesting dates due to annual weather conditions. These are based on fractions of crop and regional-specific total heat units. Whenever the fraction of total heat units for planting and harvesting is reached, planting and harvesting is triggered; the assumption in this analysis is that total heat units remain constant over time.

S2.5 Climate data

All the GGCMs used daily climate inputs except LPJ-GUESS, which used monthly climate data interpolated to daily values. GAEZ-IMAGE, LPJmL, and LPJ-GUESS use daily average temperature, while EPIC, GEPIC, pDSSAT, and PEGASUS use daily minimum and maximum temperature. For solar radiation, models use either direct surface insolation or convert this quantity to the percentage of cloud cover or the fraction of sunshine hours. EPIC and GEPIC additionally use relative humidity and wind speed in potential evapotranspiration calculations.

S2.6 Fertilizer Application

Since [CO_2] effects tend to be reduced in low nitrogen-fertility conditions (Kimball 2011), it is important to know whether the GGCMs responses to [CO_2] depend on nitrogen status (as do GEPIC and pDSSAT). The EPIC model simulated high and low input systems with respect to fertilization and irrigation by using various thresholds that trigger automatic application (see **Table S4**). GEPIC applied nitrogen and phosphorous according to FertiSTAT data. PEGASUS applied nitrogen, phosphorous, and potassium annually according to national statistics. pDSSAT applied nitrogen according to Potter et al (2010), country averages from FertiSTAT, and crop-specific management intensities from SPAM (You et al., 2000). LPJmL, LPJ-GUESS and GAEZ-IMAGE did not explicitly simulate nutrient limitations.

S2.7 Model calibration, spin-up, and outputs

GGCM differences regarding model calibration (i.e., adjustment of parameters), spin-up, and outputs may also affect analysis of the projected climate response. For example, yields from some models are reported according to the year containing the harvest date. Thus, if the harvest date falls near the start/end of the calendar year, no yields may be reported in some years but other years can report total yields for two harvests. Additionally, models with more substantial statistical calibration procedures may be affected by the implicit assumption of stationarity in climate statistics that can change dramatically over the coming century.

S2.7.1 Calibration and spin-up

The GGCM simulations differed in calibration and spin-up procedures that can also affect projected climate impacts as future climates further differentiate themselves from the historical period. When calibration was used, both variables and data sources differed. LPJmL developed calibration procedures to observed FAO average yield around the year 2000 by adjusting maximum LAI, harvest index, and a scale factor for scaling leaf-level photosynthesis to the crop stand level (Fader et al. 2010). PEGASUS calibration procedures tuned model results to M3 observed yield around 2000 (Monfreda et al., 2008) by adjusting one global parameter representing a radiation-biomass conversion factor. In the case of EPIC, crop growth parameters were not adjusted to match simulated and reported yields. Simulated yields are compared to national averages after a spin-up (nutrient mining) period of 20 years, which has been found earlier to be adequate for representing low soil nutrient status in low-input regions like sub-Saharan Africa (see Folberth et al., 2012). Other models (EPIC, pDSSAT) relied only on previous underlying site-based calibration across broad regions, while others had no calibration procedure (LPJ-GUESS) or contain a post-processing calibration procedure (GAEZ-IMAGE, but only uncalibrated yields from GAEZ-IMAGE are utilized in this study).

Crop models may better be described as including more or fewer yield-constraining factors and processes (e.g., water, nutrients, and heat stress). These yield gap issues have important implications for calibration, validation, and eventual adaptation testing (Lobell et al., 2009).

S3. Additional Results and Recommended Guidelines for Future Work

Average reference period (1980-2010) wheat, rice, and soy yields are presented in **Figures S2-S4**. **Figure S5** displays globally-aggregated production changes with CO_2 effects separated by areas that are currently rainfed and areas with irrigation. Differences in production changes between rainfed and irrigated areas in any given model are generally smaller than the differences between simulations with and without CO_2 effects.

S3.1 General recommendations for the use of GGCM ensemble results from Phase 1

The seven GGCMs that provided data to the AgMIP/ISI-MIP Phase 1 archive differ in model type, implemented mechanisms, model calibration, and implicit and explicit assumptions. These differences have strong implications for the use and interpretation of data in analyses and assessments. We here want to point out a few general caveats but request from any researcher using these data to carefully check the suitability of the data for the intended analysis. If in doubt, please contact the individual GGCM modelers.

Most obviously, some of the models have been calibrated to national or grid cell yield observations. This implies that absolute yield data are closer to observations, but it does not indicate models' skill to simulate observed yield levels. Similarly, some of the GGCMs may have been applied in specific regions more than in others and may thus have implicit assumptions that suit cropping systems in these regions better than in others. Even though some GGCMs do not capture current yield patterns well (e.g. because of lacking calibration) the simulated relative yield trends may constitute valuable information to some applications such as economic assessments, if superimposed on observed yield patterns.

Many aspects, such as sensitivity to weather extremes and year-to-year variability have not been tested in detail. Analyses on these aspects need to evaluate the models' skill in these aspects first. The AgMIP/ISI-MIP publications of Phase 1 provide a good orientation on GGCMs' performance relative to the total range of results, which should be considered in the interpretation of the data.

GGCM differences in model types, processes, inputs, and procedures imply ways that the results should be used. Relative yield changes should be used rather than absolute yield values since models differ in their calibration procedures as well as fertility inputs. For reference period yields, it is advisable to use an observation set such as the M3 data (Monfreda et al., 2008) adjusted to represent future yields using relative yield change factors calculated from the GGCMs. Furthermore, multi-year averages of yield results should be used because for some models yields are reported according to the year containing the harvest date and some years may not have reported yields or may have two harvests.

Great care should be used in interpreting regional (i.e., continental, sub-continental, national, and sub-national) results, since the objective of this study was to conduct a global-scale intercomparison, and regional input data, model settings, and results have not been vetted. (See for example the discussion of accumulation of uncertainties in Roudier et al. 2011). We recommend that detailed validation be done at national and sub-national scales as a first step to use of these results at finer-than-global scales. Work is continuing to attribute climate sensitivity differences to disparities in GGCM properties and configurations.

S3.2 AgMIP GGCM Intercomparison Phase II

In the second phase of the AgMIP GGCM intercomparison, we will conduct a rigorous validation study and design protocols that provide further information relevant to policymakers. The next phase may also include updated versions of the models described here as well as a broader range of global gridded crop models (such as DayCent, Del Grosso et al., 2001; GLAM, Challinor et al., 2004, and Osborne et al., 2013; MCWLA (Tao et al., 2009); Orchidee-Mil, Berg et al., 2013). For example, the GGCM intercomparison protocol could include simulations without nutrient limitation and with harmonized planting dates. Since economic growth is likely to spur greater fertilizer applications in current low-input regions and improve management, this would improve comparability across models and adaptation planning and may additionally be more informative than trying to match current yields in low-input regions.

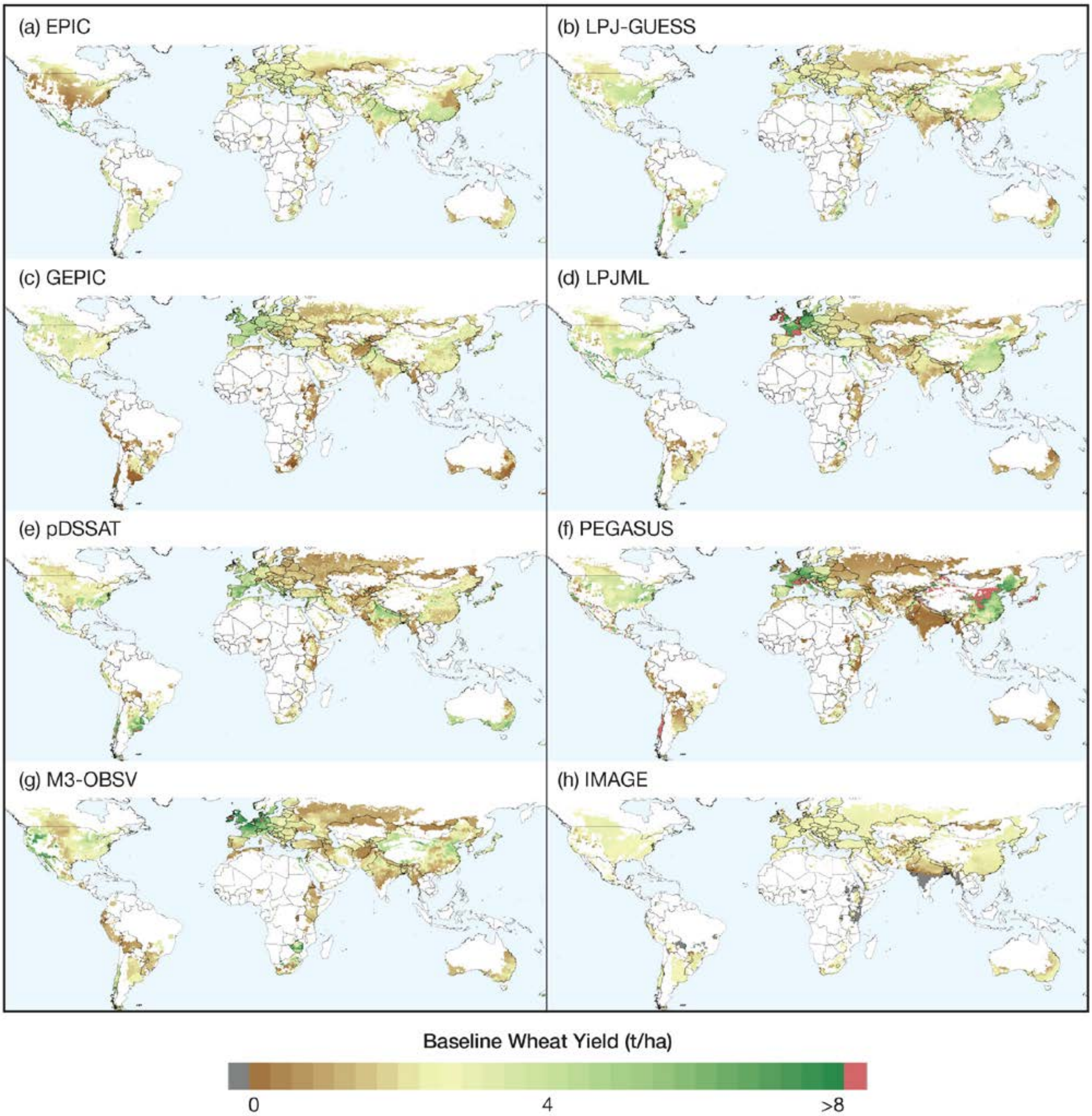

Figure S2: As in main text Figure 2, but for wheat.

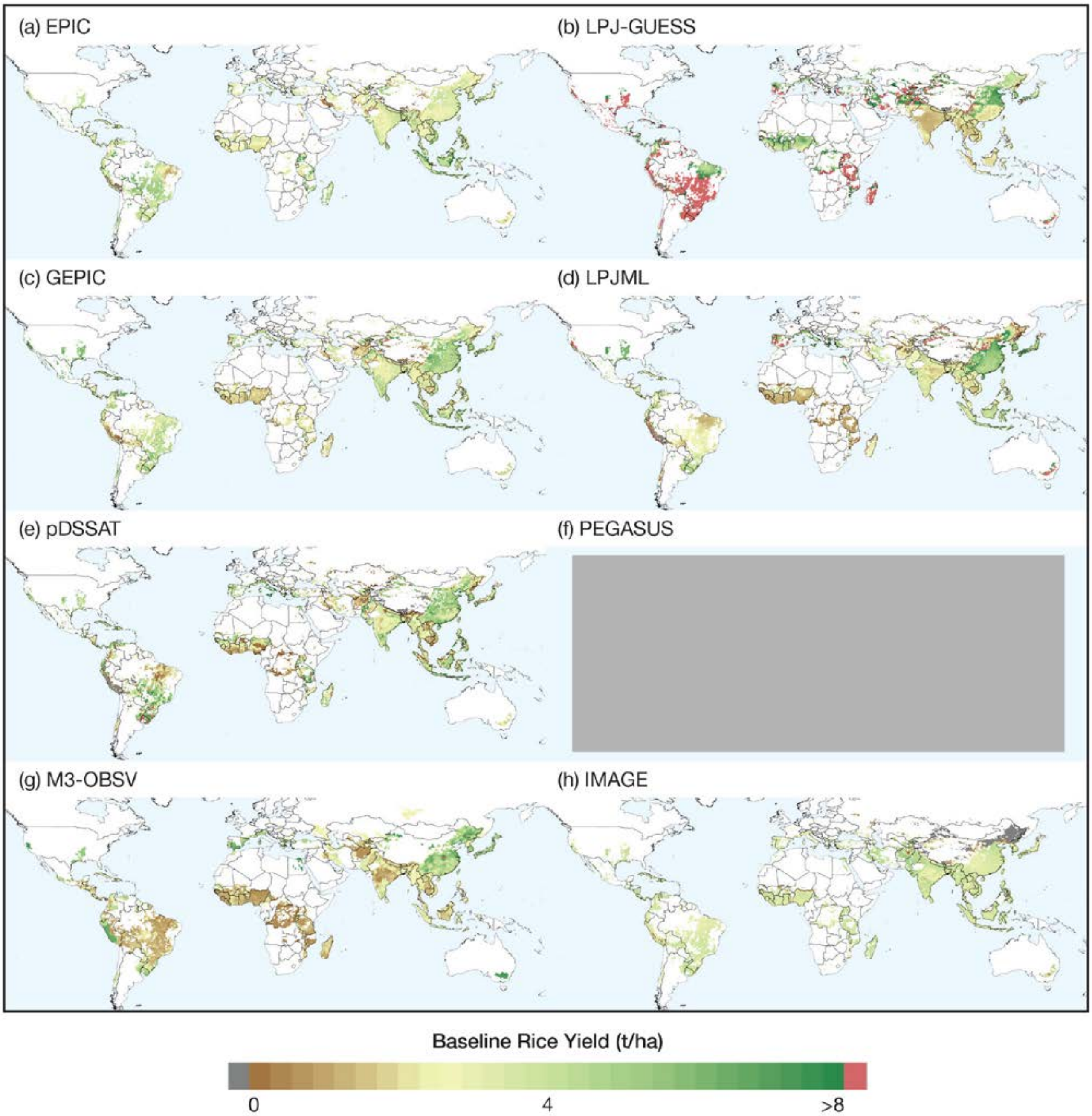

Figure S3: As in main text Figure 2, but for rice. Note that PEGASUS does not simulate rice.

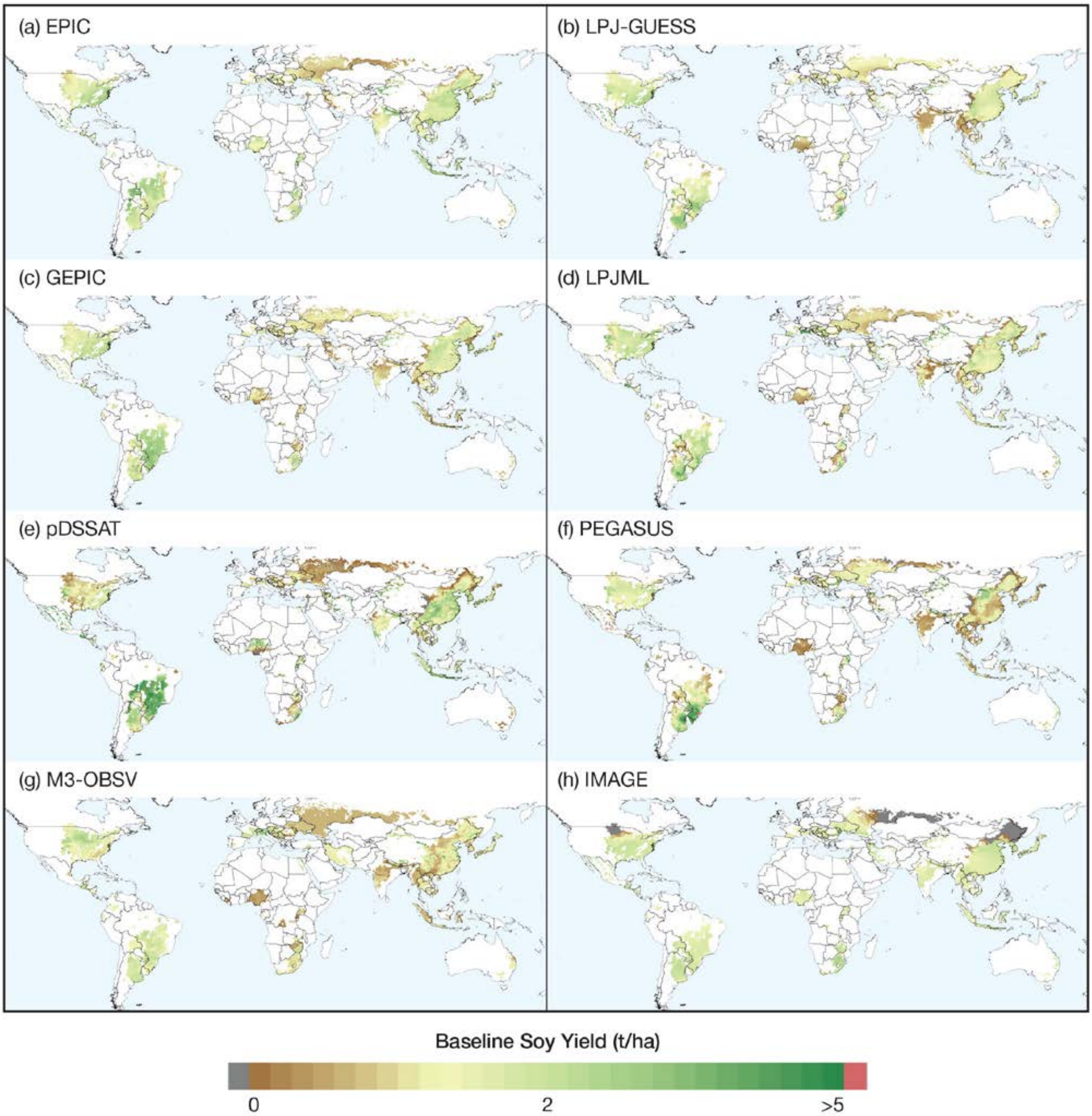

Figure S4: As in main text Figure 2, but for soybean.

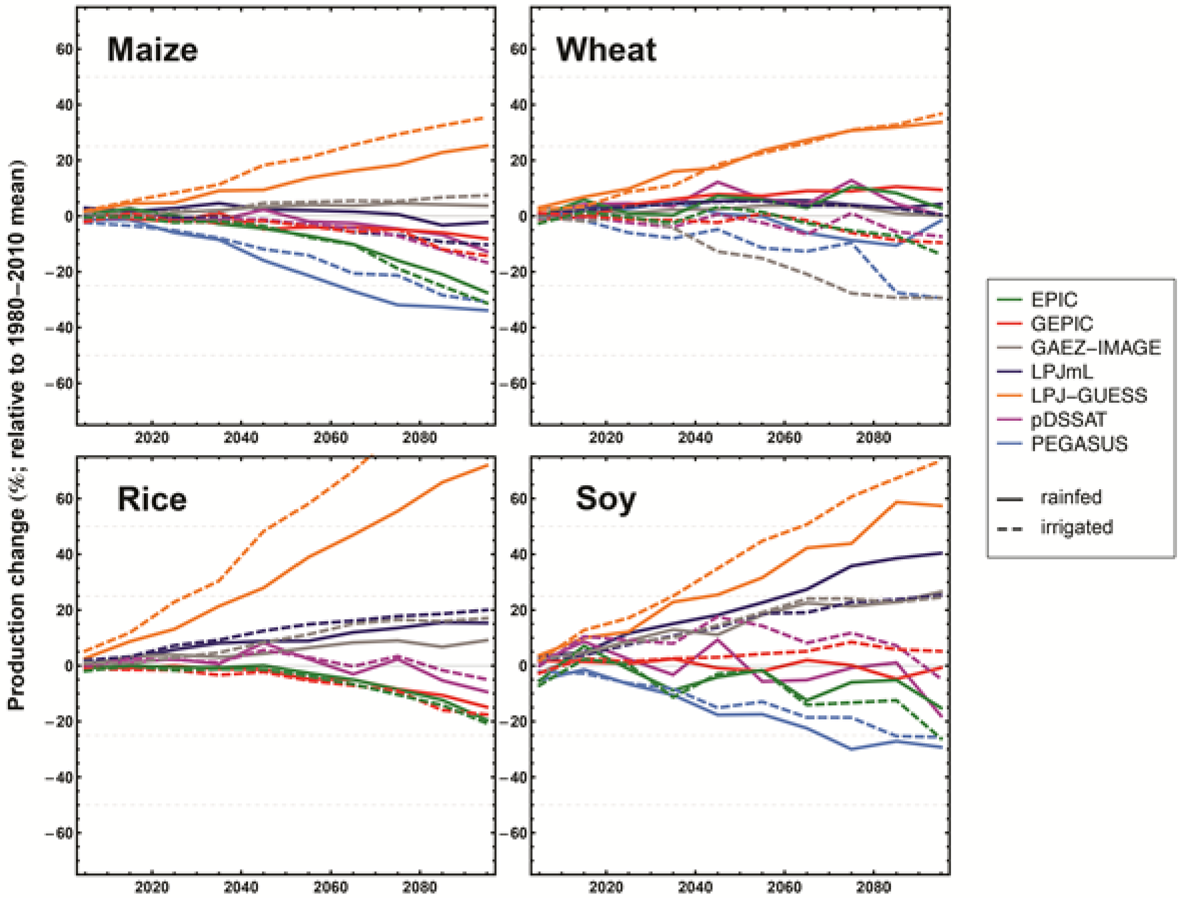

Figure S5: As in main text Figure 4, but with rainfed and irrigated areas separated with CO_2 effects.

References from Supplementary Information

1. Williams, J.R. (1995) The EPIC. In: Singh, V.P. (Ed.). Computer Models of Watershed Hydrology. Water Resources Publications. Littleton, CO. pp. 909–1000 (Chapter 25).
2. Izaurralde, R.C., et al. (2006) Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modeling 192(3-4):362-384.
3. Williams, J.R., et al. (1990) EPIC-Erosion/Productivity Impact Calculator. United States Department of Agriculture Agricultural Research Service. Technical Bulletin Number 1768. Springfield, VA.
4. Liu, J. and Williams, J and Zehnder, A.J.B. and Yang, H., (2007) GEPIC–modelling wheat yield and crop water productivity with high resolution on a global scale, Agricultural Systems, 94 (2), pp. 478–493
5. Leemans, R. and A.M. Solomon (1993) Modeling the potential change in yield and distribution of the earth's crops under a warmed climate. Climate Research 3:79-96.
6. Bouwman A.F., T. Kram, T. Klein, and K. Goldewijk (Eds.). (2006) Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4. PBL Netherlands Environmental Assessment Agency, The Hague.
7. Bondeau, A., et al. (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology 13:679–706, doi:10.1111/j.1365-2486.2006.01305.x
8. Fader, M., et al. (2010), Virtual water content of temperate cereals and maize: Present and potential future patterns, Journal of Hydrology, 384, 218-231.
9. Waha, K., et al. (2012) Climate-driven simulation of global crop sowing dates. Global Ecology and Biogeography 21:247-259.
10. Schaphoff, S., U. Heyder, S. Ostberg, D. Gerten, J. Heinke, and W. Lucht (2013) Contribution of permafrost soils to the global carbon budget, Environmental Research Letters. in press.
11. Smith, B., et al. (2001) Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. Global Ecology and Biogeography 10:621-637
12. Lindeskog M., et al. (in review) Implications of accounting for land use in simulations of ecosystem services and carbon cycling in Africa. (in review at Earth Systems Dynamics)
13. Elliott, J., M. Glotter, N. Best, D. Kelly, M. Wilde, and I. Foster (2013). The Parallel System for Integrating Impact Models and Sectors (pSIMS). Accepted for publication in the Proceedings of the 2013 XSEDE Conference.
14. Jones, J.W., et al. (2003) The DSSAT cropping system model. Eur. J. Agron. 18:235-265.
15. Deryng, D., W.J. Sacks, C.C. Barford, N. Ramankutty (2011) Simulating the effects of climate and agricultural management practices on global crop yield. Global Biogeochem. Cycles 25(2) (/doi/10.1002/gbc.v25.2/issuetoc).
16. Adam, M., van Bussel, L. G. J., Leffelaar, P. A., Van Keulen, H., and Ewert, F. (2011). Effects of modelling detail on simulated potential crop yields under a wide range of climatic conditions. Ecological Modelling, 222(1):131–143.
17. Batjes, N.H. (2006) ISRIC-WISE Derived Soil Properties on a 5 by 5 Arc-minutes Global Grid. ISRIC – World Soil Information, Wageningen, Netherlands. (Available at http://www.isric.org.)
18. Schaap, M.G., and W. Bouten (1996). Modeling water retention curves of sandy soils using neural networks. Water Resources Research, 32(10), 3033-3040.
19. van Genuchten, M.T., F. Kaveh, and W.B. Russell, W.B. (1988) Direct and indirect methods for estimating the hydraulic properties of unsaturated soils \ Land qualities in space and time : proceedings of a symposium Wageningen, the Netherlands, 22 - 26 August 1988.
20. Dobos, E. (2006) Albedo. In Encyclopedia of Soil Science, Second Edition (pp. 64-66).
21. USDA/NRCS (2012): Soil Survey Staff, Natural Resources Conservation Service, Soil Survey Geographic (SSURGO) Database for [Survey Area, State]. Available online at http://soildatamart.nrcs.usda.gov. Accessed Feb 2012.
22. Wood, S.R. and F.J. Dent (1983) LECS : a land evaluation computer system methodology. Part of: Manual / Food and Agriculture Organization Nr. no. 5, version 1
23. FAO (1991) The Digitized Soil Map of the World (Release 1.0). Food and Agriculture Organization of the United Nations)
24. FAO/IIASA/ISRIC/ISSCAS/JRC(2012) Harmonized World Soil Database (version 1.2), FAO, Rome, Italy and IIASA, Laxenburg, Austria.
25. Cosby, B.J., G.M. Hornberger, R.B. Clapp, and T.R. Ginn, T. R. (1984) A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils. Water Resources Research, 20(6), 682-690.
26. Lawrence, D.M., and A.G. Slater (2008) Incorporating organic soil into a global climate model. Climate Dynamics, 30(2-3), 145-160.
27. Sacks, W.J., D. Deryng, J.A. Foley, and N. Ramankutty (2010) Crop planting dates: an analysis of global patterns. *Global Ecology and Biogeography* 19:607-620.
28. You, L., et al. (2000) Spatial Production Allocation Model (SPAM) 2000 Version 3 Release 1. http://MapSPAM.info. (Accessed Feb, 2012).

29. Monfreda, C., Ramankutty, N. & Foley, J. A. (2008) Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. GBC 22, 19.Monteith, J.L. 1965. Evaporation and environment. Symposia of the Society for Experimental Biology 19: 205–224. PMID 5321565.
30. Willmott, C. J., et al. (1985) Statistics for the evaluation and comparison of models, J. Geophys. Res., 90(C5), 8995–9005.
31. Folberth, C., R. Gaiser, K.C. Abbaspour, R. Schulin, H. Yang (2012) Regionalization of a large-scale crop growth model for sub-Saharan Africa: Model setup, evaluation, and estimation of maize yields. *Agriculture Ecosystems & Environment* 151:21-33.
32. Farquhar, G. D., S. Caemmerer, J.A. Berry (1980) A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species. Planta 149.
33. Deryng, D., et al. (2013) Global opportunities for producing more crops per drop under rising atmospheric CO2. PNAS, submitted to this special issue.
34. Penman, H.L. (1948) Natural Evaporation from Open Water, Bare Soil and G5 Grass. Proc. Roy. Soc. London A(194), S. 120-145.
35. Monteith, J. (1965) Evaporation and environment. Symp. Soc. Exp. Biol. 19:205-234.
36. Priestley, C.H.B. and R.J. Taylor (1972) On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review 100 (2): 81–82. Bibcode 1972MWRv..100...81P. doi:10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2.
37. Hargreaves, G.H. and Z.A. Samani (1985) Reference crop evapotranspiration from temperature. *Transactions of ASAE* 1(2):96-99.
38. Baier, W. and G. W. Robertson (1965) Estimation of latent evaporation from simple weather observations. *Can. J. Plant Sci*. 45:276-284.
39. Portmann, F.T., S. Siebert, P. Doll (2010) MIRCA2000 – global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modelling. Global Biogeochemical Cycles 24:GB1011.
40. Kimball, B.A. 2011. Lessons from FACE: CO_2 effects and interactions with water, nitrogen, and temperature. In Hillel, D. and Rosenzweig, C. (Eds.). *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation*. ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol 1. Imperial College Press. London. pp. 87-107.
41. Potter, Philip, Navin Ramankutty, Elena M. Bennett, Simon D. Donner (2010) Characterizing the Spatial Patterns of Global Fertilizer Application and Manure Production. Earth Interact., 14, 1–22.
42. Lobell, D.B., K.G. Cassman, and C.B. Field (2009) Crop Yield Gaps: Their Importance, Magnitudes, and Causes. Annu. Rev. Environ. Resour. 2009. 34:179–204
43. Roudier, P., B. Sultan, P. Quirion, C. Baron, A. Alhassane, S.B. Traore, and B. Muller (2011) The impact of future climate change on West African crop yields: What does the recent literature say? Global Environmental Change 21:1073-1083.
44. Del Grosso, et al. (Eds.) (2001) Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press, Boca Raton, Florida, pp. 303-332.
45. Challinor, A.J., T.R. Wheeler, P.Q. Craufurd, J.M. Slingo, and D.I.F. Grimes (2004) Design and optimisation of a large-area process-based model for annual crops. *Agric. For. Meteorol.* 124, 99–120.
46. Osborne, T., G. Rose, and T. Wheeler (2013): Variation in the global-scale impacts of climate change on crop productivity due to climate model uncertainty and adaptation. *Agric. For. Meteorol.* 170, 183-194. doi:10.1016/j.agrformet.2012.07.006
47. Tao, F., M. Yokozawa, and Z. Zhang (2009) Modelling the impacts of weather and climate variability on crop productivity over a large area: A new process-based model development, optimization, and uncertainties analysis. *Agric. For. Meteorol.* 149, 831–850
48. Berg, A., N. de Noblet-Ducoudré, N., B. Sultan, M Lengaigne, and M. Guimberteau (2013) Projections of climate change impacts on potential C4 crop productivity over tropical regions. *Agric. For. Meteorol.* 170, 89-102. doi:10.1016/j.agrformet.2011.12.003