

The GGCMI Phase II experiment: global gridded crop model simulations under uniform changes in CO₂, temperature, water, and nitrogen levels (protocol version 1.0)

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Abstract. Concerns about food security under climate change motivate efforts to better understand future changes in crop yields. Process-based crop models, which represent plant physiological processes, are necessary tools for this purpose since they allow representing future climate and management conditions not sampled in the historical record and new locations where cultivation may shift. However, process-based crop models differ in many critical details, and their responses to different interacting factors remain only poorly understood. The Global Gridded Crop Model Intercomparison (GGCMI) Phase II

experiment, an activity of the Agricultural Model Intercomparison and Improvement Project (AgMIP), is designed to provide a systematic parameter sweep across critical interacting factors, to allow both evaluating model behavior and emulating their responses in XXX tools. In this paper we describe the GGCMI Phase II experimental protocol and its simulation data archive. Twelve crop models simulate five crops in simulations run with systematic uniform perturbations of historical climate, varying
5 CO₂, temperature, precipitation, and applied nitrogen (“CTWN”) for rainfed and irrigated agriculture. We also show some simulation results to illustrate potential uses of the GGCMI Phase II archive and general characteristics of the simulations. For example, modeled yields show robust decreases to warmer temperatures in almost all regions, with a nonlinear dependence that means yields in warmer baseline locations have greater temperature sensitivity. Inter-model uncertainty is qualitatively similar across all the four input dimensions, but is highest in high-latitude regions where crops may be grown in the future.

10 1 Introduction

Understanding crop yield response to a changing climate is critically important, especially as the global food production system will face pressure from increased demand over the next century (?). Climate-related reductions in supply could therefore have severe socioeconomic consequences (e.g. ??). Multiple studies using different crop or climate models concur in projecting sharp yield reductions on currently cultivated cropland under business-as-usual climate scenarios, although their yield
15 projections show considerable spread (e.g. ???, and references therein). Although forecasts of future yields reductions can be made with simple statistical models based on regressions in historical weather data, process-based models, which simulate the process of photosynthesis and the biology and phenology of individual crops, play a critical role in assessing the impacts of climate change.

Process-based models are necessary for understanding crop yields in novel conditions not included in historical data, including higher CO₂ levels, out-of-sample combinations of rainfall and temperature, cultivation in areas where crops are not currently grown, and differing management practices (e.g. ???). Process-based models have therefore been widely used in studies on future food security (?), options for climate mitigation (?) and adaptation (?), and future sustainable development (?). Process-based models also allow the globally gridded simulations needed for understanding the global dynamics of agricultural trade, including cultivation area changes and crop selection switching under climate change (??). These global market
25 mechanisms may strongly modulate climate change impacts (??). Global crop model experiments are therefore needed for systematic assessments (?).

Modeling crop responses continues however to be challenging, as crop growth is a function of complex interactions between climate inputs and management practices (??). Models tend to agree broadly in major response patterns, including a reasonable representation of the spatial pattern in historical yields of major crops (e.g. ??) and projections of shifts in yield under future
30 climate scenarios. But process-based models still struggle with some important details, including reproducing historical year-to-year variability in many regions (e.g. ?), reproducing historical yields when driven by reanalysis weather (e.g. ?), and low sensitivity to extreme events (e.g. ???). Long-term projections therefore retain considerable uncertainty (??????).

Model intercomparison projects such as the Agricultural Model Intercomparison and Improvement Project (AgMIP, ?) are crucial in quantifying uncertainties in model projections (?). Intercomparison projects have also been used to develop protocols for evaluating overall model performance (??) and to assess the representation of individual physical mechanisms such as water stress and CO₂ fertilization (e.g. ?). However, to date, few such projects have systematically sampled critical factors that may 5 interact strongly in affecting crop yields. A number of modeling exercises in the last five years have begun to use systematic parameter sweeps in crop model evaluation and emulation (e.g. ??????), but all involve limited sites and most also limited crops and scenarios.

The Global Gridded Crop Model Intercomparison (GGCMI) Phase II experiment is the first globally gridded crop model intercomparison involving systematic parameter sweep across critical interacting factors. GGCMI Phase II is an activity of 10 the Agricultural Model Intercomparison and Improvement Project (AgMIP), and a continuation of a multi-model comparison exercise begun in 2014. The initial GGCMI Phase I compared harmonized yield simulations over the historical period, with a primary goals of model evaluation and understanding sources of uncertainty (including model parameterization, weather inputs, and cultivation areas) (????). GGCMI Phase II compares simulations across a set of inputs with uniform perturbations to historical climatology, including CO₂, temperature, precipitation, and applied nitrogen (collectively referred to as “CTWN”), 15 as well as adaptation to shifting growing seasons. The CTWN experiment is inspired by AgMIP’s Coordinated Climate-Crop Modeling Project (C3MP ??) and contributes to the AgMIP Coordinated Global and Regional Assessments (CGRA) (??).

2 Simulation objectives and protocol

2.1 Goals

The guiding scientific rationale of GGCMI Phase II is to provide a comprehensive, systematic evaluation of the response of 20 process-based crop models to critical interacting factors, including [CO₂], temperature, water, and applied nitrogen (CTWN). The dataset is designed to allow researchers to:

- Enhance understanding of how models work by characterizing their sensitivity to input climate and nitrogen drivers.
- Study the interactions between climate variables and nitrogen inputs in driving modeled yield impacts.
- Explore differences in crop response to warming across the Earth’s climate regions.
- 25 – Provide a dataset that allows statistical emulation of crop model responses for downstream modelers.
- Illustrate differences in potential adaptation via growing season changes.

2.2 Modeling protocol

The GGCMI Phase I intercomparison was a relatively limited computational exercise, requiring yield simulations for 19 crops across a total of 310 model-years of historical scenarios, and had the participation of 21 modeling groups. The GGCMI Phase

Table 1. GGCMI Phase II input levels. Temperature and precipitation values indicate the perturbations from the historical climatology. W- percentage does not apply to the irrigated (W_{inf}) simulations, which are all simulated at the maximum beneficial levels of water. Bold font indicates the ‘baseline’ historical level. One model provided simulations at the T + 5 level. See Figure S3 in the text with each combination of input levels.

Input variable	Tested range	Unit
[CO ₂] (C)	360 , 510, 660, 810	ppm
Temperature (T)	-1, 0 , 1, 2, 3, 4, 6	°C
Precipitation (W)	-50, -30, -20, -10, 0 , 10, 20, 30, (and W_{inf})	%
Applied nitrogen (N)	10, 60, 200	kg ha ⁻¹
Adaptation (A)	A0: none , A1: new cultivar to maintain original growing season length	-

II protocol is substantially larger, involving over 1400 individual 30-year scenarios, or over 42,000 model-years; 12 modeling groups nevertheless participated. To reduce the computational load, the GGCMI Phase II protocol reduced the number crops to 5 (maize, rice, soybean, spring wheat, and winter wheat). The reduced set of crops includes the three major global cereals and the major legume and accounts for over 50% of human calories (in 2016, nearly 3.5 billion tons or 32% of total global crop production by weight) (?). This set of major crops has the advantage of historical yield data at sub-national scale across the globe (??), and has been frequently used in agricultural analyses (e.g. ??).

The Phase II protocol involves a suite of uniform perturbations from a historical weather scenario. The baseline climate scenario for GGCMI Phase II is one of the weather products used in Phase I, daily climate inputs for the years period 1980-2010 from the 0.5 degree NASA AgMERRA (“Agricultural”-modified Modern Era Retrospective analysis for Research and Applications) gridded re-analysis product. AgMERRA is specifically designed for agricultural modeling, with satellite-corrected precipitation (?). The experimental protocol consists of 9 levels for precipitation perturbations, 7 for temperature, 4 for [CO₂], and 3 for applied nitrogen, for a total of 756 simulations, 672 for rainfed agriculture and additional 84 for irrigated (Table 2.2). For irrigated simulations, models are set to eliminate all water stress, with no limitations in water supply. Values of climate variable perturbations are selected to represent reasonable ranges for changes over the medium term (to end of 2100) under business-as-usual emissions. The resulting GGCMI Phase II dataset therefore captures the distribution of crop responses over the space of future potential climate conditions.

While all perturbations are applied uniformly across the historical timeseries, they are applied in different ways. Temperature perturbations are applied as absolute offsets from the daily mean, minimum, and maximum temperature time series for each grid cell. Precipitation perturbations are applied as fractional changes at the grid cell level. [CO₂] and nitrogen levels are specified as discrete values applied uniformly over all grid cells. Perturbations are applied independently and the protocol

samples over all possible permutations. This choice means that [CO₂] changes are applied independently of changes in climate variables, so that higher [CO₂] is not associated with particular climate changes, e.g. higher temperatures.

Each model is run at 0.5 degree spatial resolution and covers all currently cultivated areas and much of the uncultivated land area. See Figure 1 for the present-day cultivated area of rainfed crops, provided by the MIRCA2000 (Montly Irrigated and Rainfed Crop Area) data product (?), and Supplementary Online Material Figure S1 in the Supplemental Material for irrigated crops. Coverage extends considerably outside currently cultivated areas because cultivation will likely shift under climate change. To reduce the computational burden, however, the protocol requires simulation only over XX% of Earth surface area. Areas are not simulated if they are assumed to remain non-arable even under an extreme climate change; these regions include Greenland, far-northern Canada, Siberia, Antarctica, the Gobi and Sahara Deserts, and central Australia. The protocol also eliminates regions judged unsuitable for cropland for non-climatic reasons. Selection criterion involve a combination of soil suitability indices at 10 arc-minute resolution and excludes those 0.5 degree grid cells in which at least 90% of the area is masked as unsuitable according to any single indexm, and which do not contain any currently cultivated cropland. Soil suitability indices measure excess salt, oxygen availability, rooting conditions, toxicities, and workability, and are provided by the IIASA (International Institute for Applied Systems Analysis) Global Agro-Ecological Zone model (GAEZ, ?). The procedure follows that proposed by ?. All modeling groups simulate the minimum required coverage, but many provide simulations that extend into masked zones, including e.g. the Sahara Desert and Central Australia.

2.3 Harmonization between models

While 10 of the 12 models participating in GGCMI Phase II use the AgMERRA historical daily climate inputs, two models require sub-daily input data and use alternative baseline climate inputs. PROMET uses the ERA-Interim reanalysis (?) at XX timescale, and JULES uses a version of ERA-Interim with modified precipitation, the XX what timescale, define acronym WFDEI (?). Explain what WFDEI does and how it's constructed. Then a Sentence about differences in temp and precip absolutes and variability between these datasets.? Did you check how much this matters to yields? Are you assuming that baseline doesn't matter and you'll still capture changes well?

While the reanalysis products agree in general, some important differences exist. For example, ERAI is approximately 1.5 °K cooler than AgMERRA in the annual means over the historical period than when aggregated over rain-fed rice cultivation area and 1 °K cooler over rain-fed maize cultivation area.

Very small differences exist in temperature and precipitation levels between AgMERRA and WFDEI for the relevant crop production areas (Figures Sxx and Syy) There are some larger differences for ERA-Interim, especially for rice area air temperatures, which are roughly 1K lower and for wheat and maize precipitation. Still, these differences are relatively small compared to the deviations used.

Growing seasons are standardized across models and assumed identical for rainfed and irrigated scenarios, but vary by crop and by location on the globe. For example, at present maize is sown in March in Spain, in July in Indonesia, and in December in Namibia. sounds like... Growing seasons are specified in terms of climatological variables, and so the actual length of crop growth alters under climate change. XX need more here. To roughly account for the importance of adaptation in agricultural

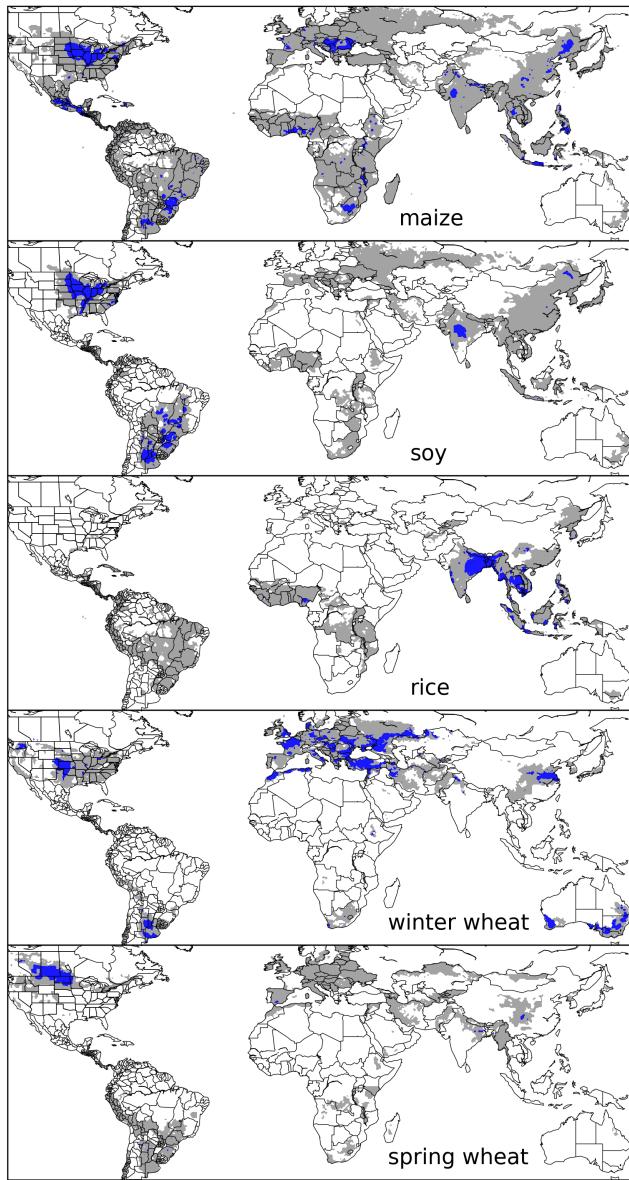


Figure 1. Presently cultivated area for rainfed crops. Blue indicates grid cells with more than 20,000 hectares ($\sim 10\%$ of an equatorial grid cell). Gray contour shows area with more than 10 hectares cultivated. Cultivated areas for maize, rice, and soybean are taken from the MIRCA2000 (“Monthly Irrigated and Rainfed Crop Areas around the year 2000”) dataset (?). Areas for winter and spring wheat areas are adapted from MIRCA2000 data and sorted by growing period; see text for details. For analogous figure of irrigated crops, see Figure S1.

production, the GGCMI Phase II protocol includes two sets of experiments that sample across planting strategies. The first set
 30 (“A0”, where A denotes “adaptation”) involves growing seasons as specified by the data sources below, which generally result in shorter growing seasons in warmer scenarios. The second set, (“A1”, with adaptation) holds the length of the growing season

fixed at that of the baseline climate scenario. These simulations roughly capture the case in which adaptive crop cultivar choice maintain the growing season length so that crops reach maturity at the same time as do current varieties under the current temperature regime. This assumption is simplistic, and does not reflect realistic opportunities and limitations to adaptation (??), but provides some insight into how crop modifications could alter projected impacts on yields.

Growing seasons for maize, rice, and soybean are taken from the SAGE crop calendar (?) and are identical to those used in GGCMI Phase I (?). In GGCMI Phase II, we separately treat spring and winter wheat and so must define different growing seasons for each. We use the SAGE crop calendar, which separately specifies spring and winter wheat, as the primary source (for XX% of grid cells. In the remaning areas where no SAGE information is available, we turn to, in order of preference, the MIRCA2000 crop calendar (?) and to simulated LPJmL growing seasons (?). These datasets each provide several options for wheat growing season for each grid cell, but do not label them as spring or winter wheat. We assign a growing season to each 5 wheat type for each location based on its baseline climate conditions. A growing seasons is assigned to winter wheat if all of the following hold:

[noitemsep]the mean monthly temperature is below freezing point ($<0^{\circ}\text{C}$) at most for 5 months per year the coldest 3 months of a year are below 10°C the season start date fits the criteria that

- - if in the N. hemisphere, it is after the warmest *or* before the coldest month of the year
10 - if in the S. hemisphere, it is after the warmest *and* before the coldest month of the year

and to spring wheat otherwise. XX Does that mean that there are only two growing seasons? does the mean monthly T criterion relate to the grid cell climatology over the whole year or to the grid cell climatology only during the growing season? also, why is there a N./S. hemisphere difference?

Nitrogen application is also standardized in timing across models. N fertilizer is applied in two doses, as is the norm in 15 actual practice, to reduce losses to the environment. In the GGCMI Phase II protocol, half of the total fertilizer input is applied at sowing and the other half on day 40 after sowing, for all crops except for winter wheat. For winter wheat, in practice the application date for the second N fertilizer application varies according to local temperature, because the length of winter dormancy can vary strongly. In the GGCMI Phase II protocol, the second fertilization date for winter wheat is set to the middle 20 day of the first month after sowing that has average temperatures above 5°C , with a minimum distance to the maturity date of 50 days and to planting of 40 days. What if these criteria disagree with each other? do you take the 50 day / 40 day limit and violate the first criterion?

All nutrient stresses are disabled in models other than those related to nitrogen, temperature, and water. For example, model 25 responses to alkalinity, salinity, and non-nitrogen nutrients are all disabled. No other external N inputs are permitted – that is, there is no atmospheric deposition of nitrogen – but some models allow additional release of plant-available nitrogen through mineralization in soils. Soil mineralization is a part of model treatments of soil organic matter and cannot be disabled. Check this, also say how many/which models have this property

2.4 Output data products

All models in GGCM Phase II provide 7 mandatory output variables (Table 1, bold), if available. For each scenario, 0.5 degree grid cell, and crop, models provide 30-year timeseries of annual crop yields in units of tons ha⁻¹ year⁻¹, as well as total aboveground biomass yield; the dates of planting, anthesis, and maturity; applied irrigation water in irrigated scenarios; and total evapotranspiration. **Did the models all provide these? Who did not provide all of them? The protocol says "if available". Whose weren't available?** Besides these mandatory 7 data products, the protocol requests any or all of 18 optional additional output variables (Table 1, plain text. Participating modeling groups provided between XX and XX of these optional variables. Finally, some models provide additional variables not specified in the protocol, such as more detailed separation of total nitrogen losses.

All output data is supplied as netCDF version 4 files, each containing values for one variable in a 30-year timeseries associated with a single scenario, for all grid cells. Filenames follow the naming conventions of GGCM Phase I (?), which themselves are adapted from **taken from?** those of ISIMIP (?). File names are specified (in small caps) as

[model]_[climate]_hist_fullharm_[irrig.scenario]_[variable]_[crop]_global_annual_[start-year]_[end-year].nc4

Here [model] is the crop model name; [climate] is the original climate input data set (typically AgMERRA); [irrig.scenario] is the irrigation setting ("fир" for fully irrigated and "noir" for fully rainfed); [variable] is the output variable (of those in Table 1); [crop] is the crop abbreviation ("mai" for maize, "ric" for rice, "soy" for soybean, "swh" for spring wheat, and "wwh" for winter wheat); and [start - year] and _[end - year] specify the first and last years recorded on file. All filenames include the identifier *global* to distinguish them as global model output.

Output data is provided on a regular geographic grid, identical for all models. Grid cell centers span latitudes -89.75 to 89.75° and longitudes from -179.75 to 179.75°. Missing values where no crop growth has been simulated are distinguished from crop failures: a crop failure is reported as zero yield but non-simulated areas (including ocean grid cells) have yields reported as 1.e+20f **what is the "f"?**. Following NetCDF standards, latitude, longitude and time are included as separate variables in ascending order, with units "degrees north", "degrees east", and "growing seasons since YYYY-01-01 00:00:00". YYYY indicates the first year of the timeseries, which is 1980 for AgMERRA **and what about the other timeseries? Also, does this contradict the statements below about reporting of years?**

XX Confusing, clarify? The first entry in the file is the result of the first simulated cropping cycle that is entirely within the given climate input. For AgMERRA, where the first year provided is 1980, the first harvest record is thus of 1980, when the prescribed sowing and harvest dates are in 1980 (e.g. sowing in March and harvest in September 1980) but is of 1981 if sowing is later in a calendar year than harvest (e.g. sowing in September 1980 and harvest in March 1981). To avoid distortions in harvest events, output files report the sequence of growing periods rather than calendar years. In most cases, this is equivalent, as there is always only one sowing event per calendar year. As harvest events are internally determined as a function of mostly temperature, these can vary between individual years. If harvest events are around the end of the calendar year (Dec. 31), reported values could contain 2 (one in early January and one in late December), 1 (normal) or none (last was in December of previous year and next is in January of the following year) harvest event if reported per calendar year.

Table 2. Output variables requested per crop in the GGCMI Phase II protocol. Items in **bold** are mandatory, if available in that model.

Variable	variable name	units
Yield	yield_<crop>	t ha⁻¹ yr⁻¹ (dry matter)
Total above ground biomass yield	biom_<crop>	t ha⁻¹ yr⁻¹ (dry matter)
Actual planting date	plant-day_<crop>	day of year
Anthesis date	anth-day_<crop>	days from planting
Maturity date	maty-day_<crop>	days from planting
Applied irrigation water	pirrww_<crop>	mm yr⁻¹
Evapotranspiration (growing season sum)	etransp_<crop>	mm yr⁻¹ (firr scenarios only)
Transpiration (growing season sum)	transp_<crop>	mm yr ⁻¹
Evaporation (growing season sum)	evap_<crop>	mm yr ⁻¹
Runoff (total growing season sum, subsurface + surface)	runoff_<crop>	mm yr ⁻¹
Total available soil moisture in root zone *	trzpah2o_<crop>	mm yr ⁻¹
Total root biomass	rootm_<crop>	t ha ⁻¹ yr ⁻¹ (dry matter)
Total Nr uptake (total growing season sum)	tnrup_<crop>	kg ha ⁻¹ yr ⁻¹
Total Nr inputs (total growing season sum)	t nrin_<crop>	kg ha ⁻¹ yr ⁻¹
Total Nr losses (total growing season sum)	t nrloss_<crop>	kg ha ⁻¹ yr ⁻¹
Gross primary production (GPP)	gpp_<crop>	gC m ⁻² yr ⁻¹
Net primary production (NPP)	npp_<crop>	gC m ⁻² yr ⁻¹
CO ₂ response scaler on NPP	co2npp_<crop>	- {0..inf}
water response scaler on NPP	h2onpp_<crop>	- {0..1}
temperature response scaler on NPP	tnpp_<crop>	- {0..1}
Nr response scaler on NPP	n rnpp_<crop>	- {0..1}
Other nutrient response scaler on NPP	or npp_<crop>	- {0..1}
CO ₂ response scaler on transpiration	co2trans_<crop>	- {0..1}
maximum stress response scaler	maxstress_<crop>	- {0..1}
Maximum LAI	laimax_<crop>	m ² m ⁻²

* growing season sum, basis for computing average soil moisture

3 Models contributing

30 The contributions of the 12 crop models supplying data to the GGCMI Phase II archive are described in Table 2. Modeling groups did not all implement the full protocol described above: given the substantial computational requirements, different participation tiers were specified to allow submission of smaller sub-sets of the full protocol. These subsets were designed as alternate samples across the 4 dimensions of the CTWN space, with *full* (12) and *low* (4) options for the C × N variables, and *full* (63), *reduced* (31), and *minimum* (9) options for T × W variables (described below). All participating modeling groups provided identical coverage of the CTWN parameter space for rainfed and irrigated scenarios, and for scenarios with and without adpatation (A0 and A1). **check**. The different participation levels are defined by combining the CxN sets with the TxW
5 sets:

- **full**: all 756 A0 simulations (all 12 CxN * all 63 TxW)
- **high**: 362 simulations (all 12 CxN combinations * *reduced* TxW set of 31 combinations)
- **mid**: 124 simulations (*low* 4 CxN combinations * *reduced* TxW set of 31 combinations)
- **low**: 36 simulations (*low* 4 CxN combinations * *minimum* TxW set of 9 combinations)

10 Why are the A1 simulations only 658 in total?

Of the 12 models submitting data, 6 followed the *full* protocol; these are marked with italic text in Table 2. However, note that two of these models (CARAIB and JULES) intrinsically cannot represent nitrogen effects and so do not sample over the the nitrogen dimension at all. 2 models followed *high* with minor modifications (XX adding an additional T level and XX omitting an N level). 1 model (XX) followed *mid* but included an additional C level. 3 models approximately folllowed *low* with XX and XX providing some additional levels and ORCHIDEE-crop omitting XX.
15

The combinations of perturbation values in the CxN and TxW parameter spaces used in the various participation levels are chosen to provide maximum coverage over plausible future values. For the CxN space, we specify

full as 12 pairs, with 3 C values (360, 660, 810 ppm) and 4 N (10, 60, XX, 200) **units**) *low* as only 4 pairs: C360_N10, C360_N200, C660_N60, C810_N200

20 For the TxW space we specify:

- *full* as all 7 T levels and 9W levels.
- *reduced* as 31 alternating combinations, with different Ws for even Ts than for odd Ts. For even Ts (i.e. T0,T2,T4,T6), we use W = -50,-20,0,+30 = 4·4 = 16 pairs. For odd Ts (i.e. T1,T3,T5) , we use W = -30, -10, +10, +30, inf = 3·5 = 15 pairs.
- *minimum* as 9 combinations: T1W-10, T0W10, T1W-30, T2W-50, T2W20, T3W30, T4W0, T4Winf, T6W-20

Table 3. Models included in GGCMI Phase II and the number of C, T, W, and N simulations that each performs, with 756 as the maximum for A0 (no adaptation) and 648 as the maximum for A1 (maintaining growing season adaptation). “N-Dim.” indicates whether the simulations include varying nitrogen levels. Two models provide only one nitrogen level. All models provide the same set of simulations across all modeled crops, but some omit individual crops. (For example, APSIM does not simulate winter wheat.)

Model (Key Citations)	Maize	Soybean	Rice	Winter wheat	Spring wheat	N dim.	Sims per crop (A0 / A1)
APSIM-UGOE, ??	X	X	X	–	X	X	44 / 36
CARAIB, ??	X	X	X	X	X	–	252 / 216
EPIC-IIASA, ?	X	X	X	X	X	X	39 / 0
EPIC-TAMU, ?	X	X	X	X	X	X	765 / 648
JULES, ???	X	X	X	–	X	–	252 / 0
GEPIC, ??	X	X	X	X	X	X	430 / 181
LPJ-GUESS, ??	X	–	–	X	X	X	756 / 648
LPJmL, ?	X	X	X	X	X	X	756 / 648
ORCHIDEE-crop,?	X	–	X	X	–	X	33 / 0
pDSSAT, ??	X	X	X	X	X	X	756 / 648
PEPIC, ??	X	X	X	X	X	X	149 / 121
PROMET, ??	X	X	X	X	X	X	261 / 232
Totals	12	10	11	11	11	10	5240 3378

The 12 models included in GGCMI Phase II are all process-based crop models that are widely used in impacts assessments (Table 2). Although some models share a common base (e.g. the LPJ family or the EPIC family of models), they have subsequently developed independently. Differences in model structure mean that several key factors are not standardized across the experiment, such as carry-over effects across growing years including residue management and soil moisture, and the extent of simulated area for different crops. Not all modeling teams provide the full simulation protocol, for instance, CARIAB and JULES do not simulate the nitrogen dimension and some crops are not parameterized in each model (see Table 2 for details).

4 Results

- 5 We provide some comparison of model results to FAO data records to describe the models’ skill in reproducing crop yield characteristics. We stress that the comparison is not straightforward as none of the settings in the CTWN-A experiment design

reflects actual conditions. For a more rigorous evaluation of the models' performance, we refer to the GGCMI model evaluation study of ?. In order to illustrate the data structure and general features of the ensemble, we show selected results in different aggregation levels (maps, regional aggregations). We focus on yield data, as this dataset if presumably of greatest interest and yield data are the more important and best evaluated outputs of GGCMs.

4.1 Simulation Assessment

5 The ? procedure evaluates response to year-to-year temperature and precipitation variations in a control run driven by historical climate and compares it to detrended historical yields from the FAO (?) by calculating the Pearson product moment correlation coefficient. The procedure is sensitive to the detrending method and the area mask used to aggregate yields. Here we use a 5-year running mean removal and the MICRA area mask for aggregation. In some cases the time series are shifted by one
10 [CO₂] has been relatively constant over the historical data collection period. Nitrogen introduces another source of uncertainty into the analysis, since the GGCMI Phase II runs impose fixed, uniform nitrogen application levels that are not realistic for individual countries. We evaluate up to three control runs for each model, since some modeling groups provide historical runs for three different nitrogen levels.

Results are similar to those of GGCMI Phase I, with reasonable fidelity at capturing year-over-year variation, with differences
15 by region and crop stronger than difference between models. (That is, Figure 2 shows more similarity in horizontal than vertical bars.) No single model is dominant, with each model providing near best-in-class performance in at least one location-crop combination. For example, maize in the United States is consistently well-simulated while maize in Indonesia is problematic (mean Pearson correlation coefficients of 0.68 and 0.18, respectively). In some cases, especially in the developing world, low correlation coefficients may indicate not only model failure but also problems in FAO yield data (??).

20 In general, correlation coefficients in GGCMI Phase II are slightly below those of Phase I, likely because of unrealistic nitrogen levels, lack of country level calibration in some models, and restriction to only the MICRA aggregation mask in this study. (Compare Figure 2 to ? Figures 1–4 and 6.) Additionally, the time period used in this case is slightly different from the time period used in ?. Note that in this methodology, simulations of crops with low year-to-year variability such as irrigated rice and wheat will tend to score more poorly than those with higher variability.

25 4.2 Simulated dynamics and data characteristics

Crop models in the GGCMI Phase II ensemble show broadly consistent responses to climate and management perturbations in most regions, with a strong negative impact of increased temperature in all but the coldest regions. Mapping the distribution of baseline yields and yield changes shows the geographic dependencies that underlie these results. Crop cultivation areas and
30 yield changes with respect to the T+4 scenario show distinct geographic pattern (Figure 3). Absolute yield potentials show strong spatial variation, with much of the Earth's surface area unsuitable for any of these crops. In general, models agree most on yield response in regions where yield potentials are currently high and therefore where crops are currently grown. Models show robust decreases in yields at low latitudes, and highly uncertain median increases at most high latitudes, due in part to how

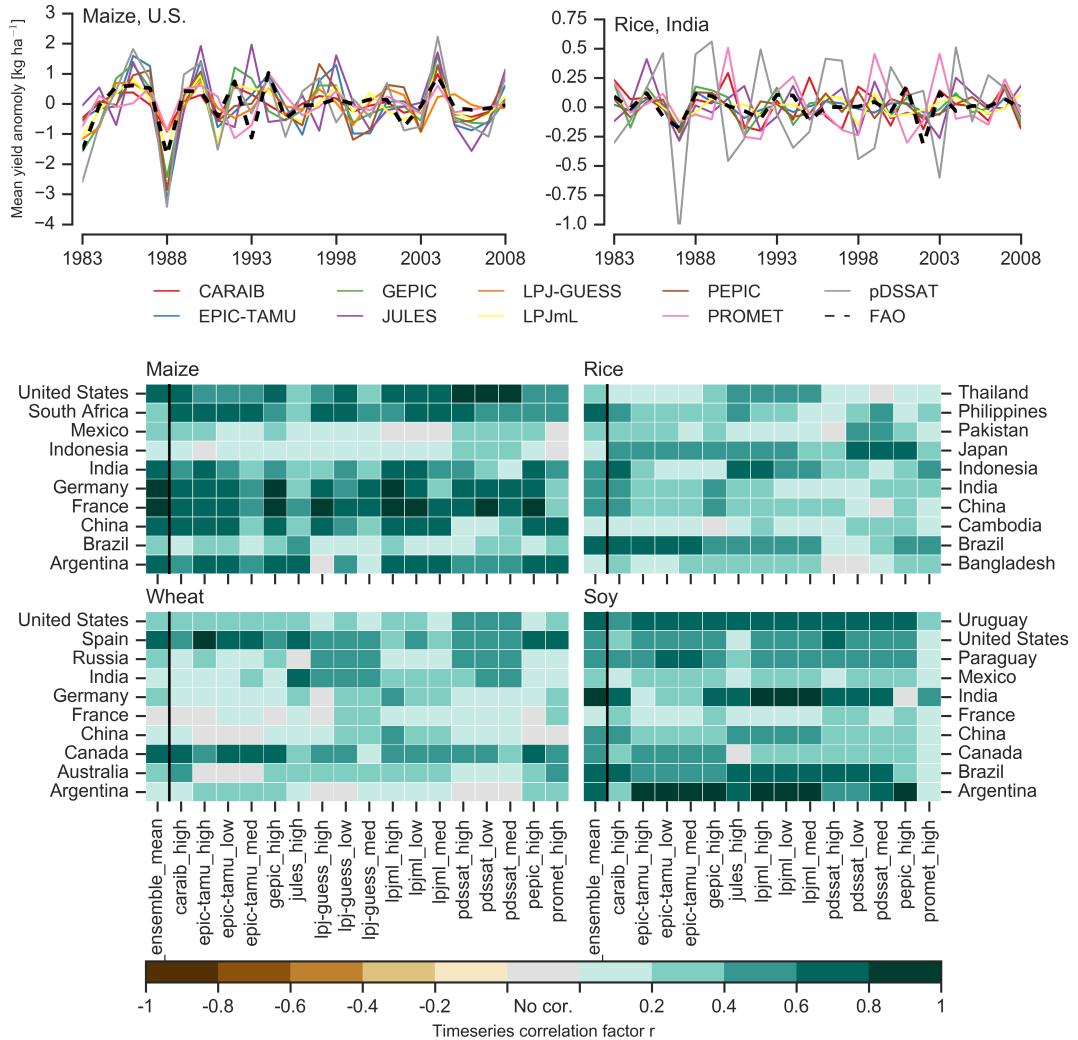


Figure 2. Time series of correlation coefficients between simulated crop yield and FAO data (?) at the country level. The top panels indicate two example cases: US maize (a good case), and rice in India (mixed case), both for the high nitrogen application case. The heatmaps illustrate the Pearson r correlation coefficient between the detrended simulation mean yield at the country level compared to the detrended FAO yield data for the top producing countries for each crop with continuous FAO data over the 1981-2010 period. Models that provided different nitrogen application levels are shown with low (10 kg N ha^{-1}), med (60 kg N ha^{-1}), and high (200 kg N ha^{-1}) label (models that did not simulate different nitrogen levels are analogous to a high nitrogen application level). The ensemble mean yield, show in the leftmost column, is also correlated with the FAO data (not the mean of the correlations). Wheat contains both spring wheat and winter wheat simulations where supplied, else one or the other (see Table 2). The Pearson r correlation coefficients are similar to those of GGCMI Phase I, with reasonable fidelity at capturing year-over-year variation, with differences by region and crop stronger than difference between models as indicated by more horizontal bars than vertical bars of the same color.

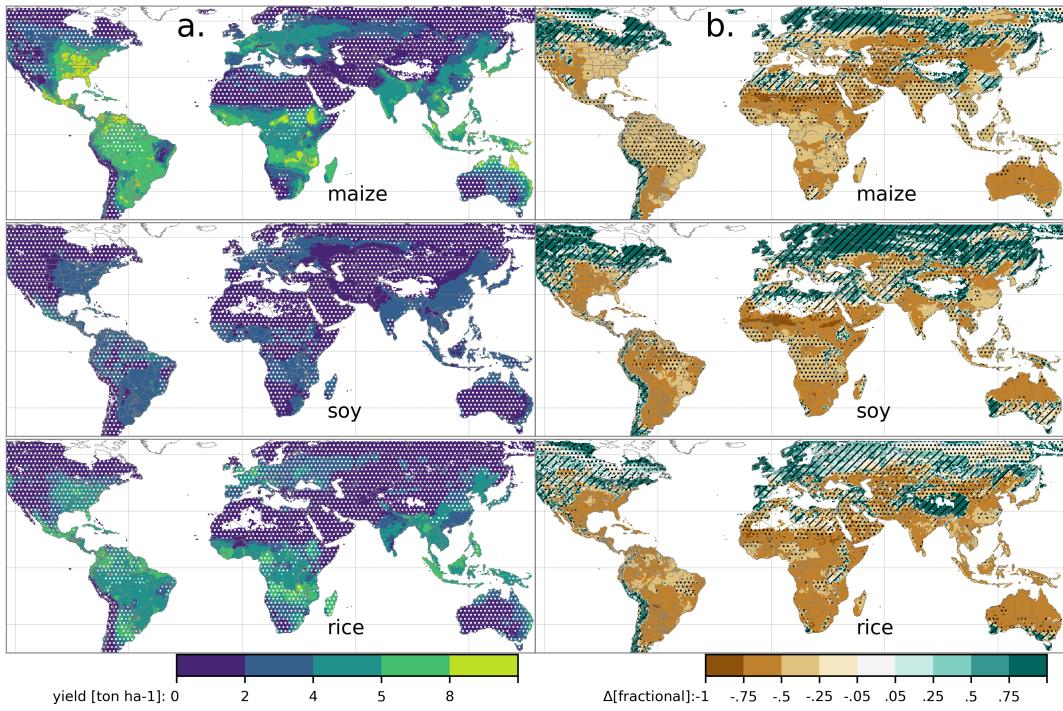


Figure 3. Illustration of the spatial pattern of potential yields and potential yield changes in the GGCMI Phase II ensemble, for three major crops: maize, soybean and rice. Left column (a) shows multi-model mean climatological yields for the baseline scenario for (top–bottom) rainfed maize, soybean, and rice. Wheat shows a qualitatively similar response, see Figure S16 in the supplemental material. White stippling indicates areas where these crops are not currently cultivated. Absence of cultivation aligns well with the lowest yield contour ($0\text{--}2 \text{ ton ha}^{-1}$). Right column (b) shows the multi-model mean fractional yield change in the $T + 4^\circ \text{C}$ scenario (with other inputs at baseline values). Areas without hatching or stippling are those where confidence in projections is high: the multi-model mean fractional change exceeds two standard deviations of the ensemble ($\Delta > 2\sigma$). Hatching indicates areas of low confidence ($\Delta < 1\sigma$), and stippling areas of medium confidence ($1\sigma < \Delta < 2\sigma$). Crop model results in cold areas, where yield impacts are on average positive, also have the highest uncertainty.

crop failures are considered across different models. This is also illustrated in Figure 4, which shows that e.g. the PROMET model has a much higher share in crop failure (yield of 0 ton ha^{-1}) at high latitudes ($>45^\circ$ north) than the LPJmL model. For wheat crops see Figure S16. Wheat projections are more uncertain, possibly because simulation calibration is especially important (e.g. ?).

Yield response differences at high latitudes are due in part to model representation of zero yields or yield failures. Model representation of crop suitability differs across models for areas where crops not currently grown. For example, soy yields north of 45° in the PROMET model are most often zero in the historical simulations and are relatively evenly distributed between 0 and 4 tons ha^{-1} in the LPJmL model. Under the warming scenario ($T+4\text{K}$), many grid cells which were previously too cold to grow soy in the PROMET model are no longer suitable and the LPJmL yields have shifted slightly down the distribution (Figure 4).

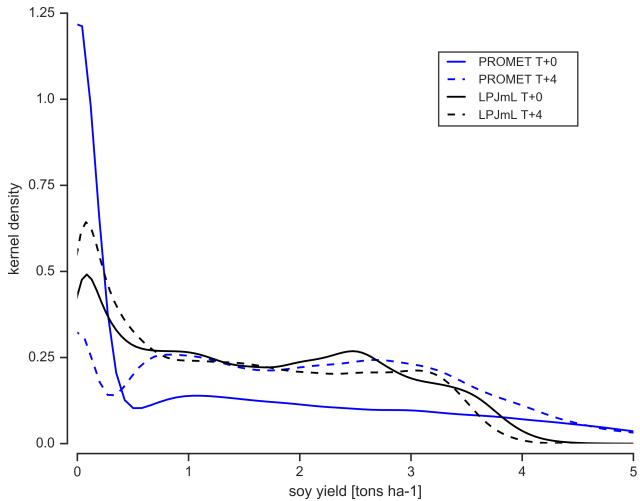


Figure 4. Kernel density estimate of soybean yields north of 45° latitude for the PROMET and LPJmL models. Solid lines show the historical climatology and dashed lines show the T+4 (K) case. Note strong reduction in the lowest bin for the T+4 case for PROMET that is spread almost equally over the rest of the distribution.

We illustrate the across-model spread for rainfed maize in Figure 5, which shows yields across all grid cells for the primary
 10 Köppen-Geiger climate regions (?). In warming scenarios with precipitation held constant, all models show decreases in maize
 yield in the ‘warm temperate’, ‘equatorial’, and ‘arid’ regions that account for nearly three-quarters of global maize production.
 These impacts are robust for even moderate climate perturbations. In the ‘warm temperate’ zone, even a 1 degree temperature
 rise with other variables held fixed leads to a median yield reduction that exceeds the variance across models. A 6 degree
 5 temperature rise results in median loss of $\sim 25\%$ of yields with a signal to noise ratio of nearly three to one. A notable
 exception is the ‘cold continental’ region, where models disagree strongly, extending even to the sign of impacts. Other crops
 show similar responses to warming, with robust yield losses in warmer locations and high inter-model variance in the ‘cold
 continental’ regions (Figure S5).

The effects of rainfall changes on maize yields shown in Figure 5 (and for soybean in Figure ??) are also relatively consistent across models. Increased rainfall mitigates the negative effect of higher temperatures by counteracting the increased
 10 evapo-transpiration to some degree, most strongly in arid regions. Decreased rainfall amplifies yield losses and also increases inter-model variance; i.e. models agree that the response to decreased water availability is negative in sign but disagree on its magnitude. Increased temperature results in a relative flattening of the precipitation change response (Figure ??). We show only rainfed maize and soy here; see Figure S6 for comparison between rainfed and irrigated maize. As expected, irrigated crops are more resilient to temperature increases in all regions, especially so where water is limiting. See Figures S7-15 in the
 15 supplement for other crops.

Mean climatological yield response to the other two dimensions (C and N) are qualitatively similar. The yield response to increased CO₂ for spring wheat is a robust increase across models in all climate regions (Figure ??). Increased precipitation

allows crops to capture additional yield boost from elevated CO₂ levels in the mid range in most climate regions, but this effect saturates at the highest CO₂ levels. Increased CO₂ outweighs the damages caused by 20% reduced precipitation in all climate regions in the multi-model median, but not all models agree upon the positive sign.

5 Discussion and Conclusions

5 This must not be confused with a correct historic setup, as there is no trend in the [CO₂] and the uniform application of 200 kg N ha⁻¹ is not representative for many world regions (?). The GGCMI Phase II simulations are designed for evaluating changes in yield across the CTNW-A space but not necessarily absolute yields, since they omit detailed calibrations. To provide some evaluation of the skill of the process-based models used, we repeat the evaluation exercises of ? for GGCMI Phase I but stress that in particular the uniform fertilizer application does not represent the actual situation. The GGCMI Phase II
10 experiment provides a database designed to allow detailed study of crop yields from process-based models under climate change. The use of systematic input parameter variations facilitates not only comparing the sensitivities of process-based crop yield models to changing climate and management inputs but also evaluating the complex interactions between driving factors ([CO₂], temperature, precipitation, and applied nitrogen). Its global extent also allows identifying geographic shifts in high yield potential locations. We expect that the simulations will yield multiple insights in future studies, and show a selection of
15 preliminary results. We discuss below the implications from the experimental design, but refrain from analyzing simulation results in detail. Data analyses will be conducted in subsequent analyses making use of the GGCMI Phase II data archive.

First, the GGCMI Phase II simulations allow identifying major areas of uncertainty. Inter-model uncertainty is qualitatively similar across all four inputs tested at the globally aggregate level with some notable exceptions. For example, soybean, a nitrogen-fixing legume, is insensitive to nitrogen addition, while wheat is particularly uncertain in its response to [CO₂] levels
20 and water availability (Figure S22). Across geographic regions, projections are most robust in the low latitudes where yield impacts are largest, and most uncertain in the high latitudes where yields may increase under warming. Model differences in projected high-latitude yield changes appear driven more by differences in baseline than in responses to CTWN perturbations. PROMET, for example, involves a stronger response to cold than does LPJmL, with frost below -8 °C irreversibly killing non-winter crops and prolonged periods of below-optimum temperatures also leading to complete crop failure. Over the high-
25 latitudes regions simulated by both models, 52% of grid cells in PROMET report 0 yield in the present climate vs. 11% of cells in the T+4 scenario, leading to a strong yield gain in warmer future climates. In LPJmL outputs, the same high-latitude area is deemed suitable for cultivation even in baseline climate, with crop failure rates of 4% and 5% in present and T+4 cases, so that projected yield changes are modest (Figure 4.)

Second, the GGCMI Phase II simulations demonstrate the sensitivity of climate-driven yield impacts to the locations of cultivated land. One counterintuitive result apparent in the simulations is that warmer temperatures drive steeper yield reductions in irrigated than rainfed maize when considered only over currently cultivated land, even though water availability increases crop resiliency to temperature increases at any given location (compare Figure 5 and Figures S6 to S7). The effect results from geographic differences in cultivation: irrigated maize is grown in warmer locations where the impacts of warming are more severe
30

(See Figures S8-S15 for other crops.) Geographic effects also mean that nitrogen fertilization produces stronger responses in irrigated than non-irrigated wheat and maize, presumably because those rainfed crops are limited by water availability (Figure S21).

In general, the development of multi-model ensembles involving systematic parameters sweeps has large promise for increasing understanding of potential future crop responses and for improving process-based crop models. The data set is unprecedentedly large, being global in extent, covering 31-simulation years per pixel and up to 756 perturbations for 12 GGCMS. We expect that the GGCMI Phase II data archive will be used to analyze the different GGCMS' sensitivity to changes in the CTWN-A space, including the interaction between drivers. The authors are working on some analyses but many more are facilitated by the GGCMI Phase II data archive.

- 10 *Code and data availability.* The simulation outputs of the mandatory 7 output variables (Table 1) are available on zenodo.org. See Appendix A1 for data DOIs. All other simulation output variables are available upon request to the corresponding author. The scripts for generating the spring wheat and winter wheat growing seasons and second fertilizer dates and the quality screening script is available at <https://github.com/RDCEP/ggcmi/blob/phase2/>. All input data are available via globus.org (registration required, free of charge): Minimum cropland mask is available at https://www.globus.org/app/transfer?origin_id=e4c16e81-6d04-11e5-ba46-22000b92c6ec&origin_path=%2FAGMIP.input%2FCTWN%2F choose the file boolean_cropmask_ggcmi_phase2.nc4 Growing period data for wheat is now divided up into winter and spring wheat, available at https://www.globus.org/app/transfer?origin_id=e4c16e81-6d04-11e5-ba46-22000b92c6ec&origin_path=%2FAGMIP.input%2Fother.inputs%2FAGMIP_GROWING_SEASON.HARM.version2.0%2F whereas all other growing season data (maize, rice, soybean) are the same as in Phase I (version 1.25), available at https://www.globus.org/app/transfer?origin_id=e4c16e81-6d04-11e5-ba46-22000b92c6ec&origin_path=%2Fother.inputs%2FAGMIP_GROWING_SEASON.HARM.version1.25%2F
- 15 20 25%2F

Appendix A

A1 Data Access

Simulation yield output datasets can be found at the DOIs located in table A1. Data are published in crop- and GGCMM-specific packages, in order to break down the overall data amount into manageable packages (<50GB per archive).

- 25 *Author contributions.* J.E., C.M., and A.R. designed the research. C.M., J.J., J.B., P.C., M.D., P.F., C.F., L.F., M.H., C.I., I.J., C.J., N.K., M.K., W.L., S.O., M.P., T.P., A.R., X.W., K.W., and F.Z. performed the simulations. J.F., J.J., A.S., M.L., C.M., and E.M. performed the analysis and J.F., E.M., and C.M. prepared the manuscript.

Competing interests. The authors declare no competing interests.

Table A1. DOI's for model yield data outputs. All yield output data can be found at <https://doi.org/10.5281/zenodo/XX>. Where XX is the value found in the table.

Model	Maize	Soybean	Rice	Winter wheat	Spring wheat
APSIM-UGOE	2582531	2582535	2582533	2582537	2582539
CARAIB	2582522	2582508	2582504	2582516	2582499
EPIC-IIASA	2582453	2582461	2582457	2582463	2582465
EPIC-TAMU	2582349	2582367	2582352	2582392	2582418
JULES	2582543	2582547	2582545	–	2582551
GEPIC	2582247	2582258	2582251	2582260	2582263
LPJ-GUESS	2581625	–	–	2581638	2581640
LPJmL	2581356	2581498	2581436	2581565	2581606
ORCHIDEE-crop	2582441	–	2582445	2582449	–
pDSSAT	2582111	2582147	2582127	2582163	2582178
PEPIC	2582341	2582433	2582343	2582439	2582455
PROMET	2582467	2582488	2582479	2582490	2582492

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References

- Angulo, C., Rötter, R., Lock, R., Enders, A., Fronzek, S., and Ewert, F.: Implication of crop model calibration strategies for assessing regional impacts of climate change in Europe, *Agric. For. Meteorol.*, 170, 32 – 46, <https://doi.org/10.1016/j.agrformet.2012.11.017>, 2013.
- 365 Asseng, S., Ewert, F., Rosenzweig, C., Jones, J., Hatfield, J., Ruane, A., J. Boote, K., Thorburn, P., Rötter, R. P., Cammarano, D., Brisson, N., Basso, B., Martre, P., Aggarwal, P., Angulo, C., Bertuzzi, P., Biernath, C., Challinor, A., Doltra, J., Gayler, S., Goldberg, R., Grant, R., Heng, L., Hooker, J., Hunt, L. A., Ingwersen, J., Izaurrealde, R. C., Kersebaum, K. C., Müller, C., Kumar, S. N., Nendel, C., Leary, G. O., Olesen, J. E., Osborne, T. M., Palosuo, T., Priesack, E., Riponche, D., Semenov, M. A., Shcherbak, I., Steduto, P., Stöckle, C., Strattonovitch, P., Streck, T., Supit, I., Tao, F., Travasso, M., Waha, K., Wallach, D., Williams, J. R., and Wolf, J.: Uncertainty in simulating wheat yields under climate change, *Nature Climate Change*, 3, 827–832, <https://doi.org/10.1038/nclimate1916>, 2013.
- 370 Asseng, S., Ewert, F., Martre, P., Rötter, R. P., B. Lobell, D., Cammarano, D., A. Kimball, B., Ottman, M., W. Wall, G., White, J., Reynolds, M., D. Alderman, P., Prasad, P. V. V., Aggarwal, P., Anothai, J., Basso, B., Biernath, C., Challinor, A., De Sanctis, G., Doltra, J., Fereres, E., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L. A., Izaurrealde, R. C., Jabloun, M., Jones, C. D., Kersebaum, K. C., Koehler, A.-K., Muller, C., Naresh Kumar, S., Nendel, C., O'Leary, G., Olesen, J. E., Palosuo, T., Priesack, E., Eyshi Rezaei, E., Ruane, A. C., Semenov, M. A., Shcherbak, I., Stockle, C., Strattonovitch, P., Streck, T., Supit, I., Tao, F., Thorburn, P. J., Waha, K., Wang, E., Wallach, D., Wolf, J., Zhao, Z., and Zhu, Y.: Rising temperatures reduce global wheat production, *Nature Climate Change*, 5, 143–147, <https://doi.org/10.1038/nclimate2470>, 2015.
- Balkovič, J., van der Velde, M., Skalský, R., Xiong, W., Folberth, C., Khabarov, N., Smirnov, A., Mueller, N. D., and Obersteiner, M.: Global wheat production potentials and management flexibility under the representative concentration pathways, *Global and Planetary Change*, 122, 107 – 121, <https://doi.org/10.1016/j.gloplacha.2014.08.010>, 2014.
- 380 Bodirsky, B. L., Rolinski, S., Biewald, A., Weindl, I., Popp, A., and Lotze-Campen, H.: Global Food Demand Scenarios for the 21st Century, *PLOS ONE*, 10, 1–27, <https://doi.org/10.1371/journal.pone.0139201>, <https://doi.org/10.1371/journal.pone.0139201>, 2015.
- Challinor, A. J., Müller, C., Asseng, S., Deva, C., Nicklin, K. J., Wallach, D., Vanuytrecht, E., Whitfield, S., Ramirez-Villegas, J., and Koehler, A.-K.: Improving the use of crop models for risk assessment and climate change adaptation, *Agricultural systems*, 159, 296–306, 2018.
- 385 Dee, D. P., Uppala, S., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G., Bauer, d. P., et al.: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, *Quarterly Journal of the royal meteorological society*, 137, 553–597, 2011.
- Dury, M., Hambuckers, A., Warnant, P., Henrot, A., Favre, E., Ouberdoos, M., and François, L.: Responses of European forest ecosystems to 21st century climate: assessing changes in interannual variability and fire intensity, *iForest - Biogeosciences and Forestry*, pp. 82–99, <https://doi.org/10.3832/ifor0572-004>, 2011.
- 390 Elliott, J., Kelly, D., Chryssanthacopoulos, J., Glotter, M., Jhunjhnuwala, K., Best, N., Wilde, M., and Foster, I.: The parallel system for integrating impact models and sectors (pSIMS), *Environmental Modelling and Software*, 62, 509–516, <https://doi.org/10.1016/j.envsoft.2014.04.008>, 2014.
- Elliott, J., Müller, C., Deryng, D., Chryssanthacopoulos, J., Boote, K. J., Büchner, M., Foster, I., Glotter, M., Heinke, J., Iizumi, T., Izaurrealde, R. C., Mueller, N. D., Ray, D. K., Rosenzweig, C., Ruane, A. C., and Sheffield, J.: The Global Gridded Crop Model Intercomparison: data and modeling protocols for Phase 1 (v1.0), *Geoscientific Model Development*, 8, 261–277, <https://doi.org/10.5194/gmd-2016-207>, 2015.
- 395 FAO/IIASA: Global Agro-ecological Zones and FAO-GAEZ Data Portal(GAEZ v3.0), <http://www.gaez.iiasa.ac.at/>, 2011.

- Folberth, C., Gaiser, T., Abbaspour, K. C., Schulin, R., and Yang, H.: 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, 400 <https://doi.org/10.1016/j.agee.2012.01.026>, 2012.
- Folberth, C., Elliott, J., Müller, C., Balkovic, J., Chryssanthacopoulos, J., Izaurrealde, R. C., Jones, C. D., Khabarov, N., Liu, W., Reddy, A., Schmid, E., Skalský, R., Yang, H., Arneth, A., Ciais, P., Deryng, D., Lawrence, P. J., Olin, S., Pugh, T. A. M., Ruane, A. C., and Wang, X.: Uncertainties in global crop model frameworks: effects of cultivar distribution, crop management and soil handling on crop yield estimates, *Biogeosciences Discussions*, 2016, 1–30, <https://doi.org/10.5194/bg-2016-527>, <https://www.biogeosciences-discuss.net/bg-2016-527/>, 2016.
- Food and Agriculture Organization of the United Nations: FAOSTAT Database, <http://www.fao.org/faostat/en/home>, 2018.
- Frieler, K., Lange, S., Piontek, F., Reyer, C. P., Schewe, J., Warszawski, L., Zhao, F., Chini, L., Denvil, S., Emanuel, K., et al.: Assessing the impacts of 1.5 C global warming—simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b), *Geoscientific Model Development*, 2017.
- 410 Fronzek, S., Pirttioja, N., Carter, T. R., Bindi, M., Hoffmann, H., Palosuo, T., Ruiz-Ramos, M., Tao, F., Trnka, M., Acutis, M., Asseng, S., Baranowski, P., Basso, B., Bodin, P., Buis, S., Cammarano, D., Deligios, P., Destain, M.-F., Dumont, B., Ewert, F., Ferrise, R., François, L., Gaiser, T., Hlavinka, P., Jacquemin, I., Kersebaum, K. C., Kollas, C., Krzyszczak, J., Lorite, I. J., Minet, J., Minguez, M. I., Montesino, M., Moriondo, M., Müller, C., Nendel, C., Öztürk, I., Perego, A., Rodríguez, A., Ruane, A. C., Ruget, F., Sanna, M., Semenov, M. A., Slawinski, C., Stratonovitch, P., Supit, I., Waha, K., Wang, E., Wu, L., Zhao, Z., and Rötter, R. P.: Classifying multi-model wheat yield impact response surfaces showing sensitivity to temperature and precipitation change, *Agricultural Systems*, 159, 209–224, <https://doi.org/10.1016/j.agsy.2017.08.004>, 2018.
- Glotter, M., Elliott, J., McInerney, D., Best, N., Foster, I., and Moyer, E. J.: Evaluating the utility of dynamical downscaling in agricultural impacts projections, *Proceedings of the National Academy of Sciences*, 111, 8776–8781, <https://doi.org/10.1073/pnas.1314787111>, 2014.
- Glotter, M., Moyer, E., Ruane, A., and Elliott, J.: Evaluating the Sensitivity of Agricultural Model Performance to Different Climate Inputs, 420 *Journal of Applied Meteorology and Climatology*, 55, 151113145618 001, <https://doi.org/10.1175/JAMC-D-15-0120.1>, 2015.
- Hank, T., Bach, H., and Mauser, W.: Using a Remote Sensing-Supported Hydro-Agroecological Model for Field-Scale Simulation of Heterogeneous Crop Growth and Yield: Application for Wheat in Central Europe, *Remote Sensing*, 7, 3934–3965, <https://doi.org/10.3390/rs70403934>, 2015.
- Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B. L., Doelman, J. C., Fellmann, T., Kyle, P., Koopman, J. F., Lotze-Campen, H., 425 et al.: Risk of increased food insecurity under stringent global climate change mitigation policy, *Nature Climate Change*, 8, 699, 2018.
- Holzworth, D. P., Huth, N. I., deVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., Chenu, K., van Oosterom, E. J., Snow, V., Murphy, C., Moore, A. D., Brown, H., Whish, J. P., Verrall, S., Fainges, J., Bell, L. W., Peake, A. S., Poulton, P. L., Hochman, Z., Thorburn, P. J., Gaydon, D. S., Dalgliesh, N. P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F. Y., Wang, E., Hammer, G. L., Robertson, M. J., Dimes, J. P., Whitbread, A. M., Hunt, J., van Rees, H., McClelland, T., Carberry, P. S., Hargreaves, J. N., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., and Keating, B. A.: AP-SIM – Evolution towards a new generation of agricultural systems simulation, *Environmental Modelling and Software*, 62, 327 – 350, 430 <https://doi.org/10.1016/j.envsoft.2014.07.009>, 2014.
- Humpenöder, F., Popp, A., Bodirsky, B. L., Weindl, I., Biewald, A., Lotze-Campen, H., Dietrich, J. P., Klein, D., Kreidenweis, U., Müller, C., et al.: Large-scale bioenergy production: how to resolve sustainability trade-offs?, *Environmental Research Letters*, 13, 024011, 2018.

- 435 Iizumi, T., Nishimori, M., and Yokozawa, M.: Diagnostics of Climate Model Biases in Summer Temperature and Warm-Season Inso-
lation for the Simulation of Regional Paddy Rice Yield in Japan, *Journal of Applied Meteorology and Climatology*, 49, 574–591,
<https://doi.org/10.1175/2009JAMC2225.1>, 2010.
- Iizumi, T., Yokozawa, M., Sakurai, G., Travasso, M. I., Romanenkov, V., Oettli, P., Newby, T., Ishigooka, Y., and Furuya, J.: Histor-
ical changes in global yields: major cereal and legume crops from 1982 to 2006, *Global Ecology and Biogeography*, 23, 346–357,
440 <https://doi.org/10.1111/geb.12120>, 2014.
- Izaurrealde, R., Williams, J., McGill, W., Rosenberg, N., and Quiroga Jakas, M.: Simulating soil C dynamics with EPIC: Model description
and testing against long-term data, *Ecological Modelling*, 192, 362–384, <https://doi.org/10.1016/j.ecolmodel.2005.07.010>, 2006.
- J. Boote, K., Jones, J., White, J., Asseng, S., and Lizaso, J.: Putting Mechanisms into Crop Production Models., *Plant, cell & environment*,
36, <https://doi.org/10.1111/pce.12119>, 2013.
- 445 Jägermeyr, J. and Frieler, K.: Spatial variations in crop growing seasons pivotal to reproduce global fluctuations in maize and wheat yields,
Science Advances, 4, 4517, <https://doi.org/10.1126/sciadv.aat4517>, 2018.
- Jagtap, S. S. and Jones, J. W.: Adaptation and evaluation of the CROPGRO-soybean model to predict regional yield and production, *Agri-
culture, Ecosystems & Environment*, 93, 73 – 85, [https://doi.org/10.1016/S0167-8809\(01\)00358-9](https://doi.org/10.1016/S0167-8809(01)00358-9), 2002.
- Jones, J., Hoogenboom, G., Porter, C., Boote, K., Batchelor, W., Hunt, L., Wilkens, P., Singh, U., Gijsman, A., and Ritchie, J.: The DSSAT
450 cropping system model, *European Journal of Agronomy*, 18, 235 – 265, [https://doi.org/10.1016/S1161-0301\(02\)00107-7](https://doi.org/10.1016/S1161-0301(02)00107-7), 2003.
- Keating, B., Carberry, P., Hammer, G., Probert, M., Robertson, M., Holzworth, D., Huth, N., Hargreaves, J., Meinke, H., Hochman, Z.,
McLean, G., Verburg, K., Snow, V., Dimes, J., Silburn, M., Wang, E., Brown, S., Bristow, K., Asseng, S., Chapman, S., McCown, R.,
Freebairn, D., and Smith, C.: An overview of APSIM, a model designed for farming systems simulation, *European Journal of Agronomy*,
18, 267 – 288, [https://doi.org/10.1016/S1161-0301\(02\)00108-9](https://doi.org/10.1016/S1161-0301(02)00108-9), 2003.
- 455 Lindeskog, M., Arneth, A., Bondeau, A., Waha, K., Seaquist, J., Olin, S., and Smith, B.: Implications of accounting for land use in simulations
of ecosystem carbon cycling in Africa, *Earth System Dynamics*, 4, 385–407, <https://doi.org/10.5194/esd-4-385-2013>, 2013.
- Liu, J., Williams, J. R., Zehnder, A. J., and Yang, H.: GEPIC - modelling wheat yield and crop water productivity with high resolution on a
global scale, *Agricultural Systems*, 94, 478 – 493, <https://doi.org/10.1016/j.agsy.2006.11.019>, 2007.
- Liu, W., Yang, H., Folberth, C., Wang, X., Luo, Q., and Schulin, R.: Global investigation of impacts of PET methods on simulating crop-water
460 relations for maize, *Agricultural and Forest Meteorology*, 221, 164 – 175, <https://doi.org/10.1016/j.agrformet.2016.02.017>, 2016a.
- Liu, W., Yang, H., Liu, J., Azevedo, L. B., Wang, X., Xu, Z., Abbaspour, K. C., and Schulin, R.: Global assessment of ni-
trogen losses and trade-offs with yields from major crop cultivations, *Science of The Total Environment*, 572, 526 – 537,
<https://doi.org/10.1016/j.scitotenv.2016.08.093>, 2016b.
- Makowski, D., Asseng, S., Ewert, F., Bassu, S., Durand, J., Martre, P., Adam, M., Aggarwal, P., Angulo, C., Baron, C., Basso, B., Bertuzzi,
465 P., Biernath, C., Boogaard, H., Boote, K., Brisson, N., Cammarano, D., Challinor, A., Conijn, J., and Wolf, J.: Statistical Analysis of Large
Simulated Yield Datasets for Studying Climate Effects, p. 1100, <https://doi.org/10.13140/RG.2.1.5173.8328>, 2015.
- Mauser, W., Klepper, G., Zabel, F., Delzeit, R., Hank, T., Putzenlechner, B., and Calzadilla, A.: Global biomass production potentials exceed
expected future demand without the need for cropland expansion, *Nature Communications*, 6, <https://doi.org/10.1038/ncomms9946>, 2015.
- McDermid, S. P., Ruane, A. C., Rosenzweig, C., Hudson, N. I., Morales, M. D., Agalawatte, P., Ahmad, S., Ahuja, L., Amien, I., Anapalli,
470 S. S., et al.: The AgMIP coordinated climate-crop modeling project (C3MP): methods and protocols, in: *HANDBOOK OF CLIMATE
CHANGE AND AGROECOSYSTEMS: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Eco-
nomic Assessments*, Part 1, pp. 191–220, World Scientific, 2015.

- Minoli, S., Egli, D. B., Rolinski, S., and Müller, C.: Modelling cropping periods of grain crops at the global scale, *Global and Planetary Change*, 174, 35–46, 2019.
- 475 Müller, C., Elliott, J., Chryssanthacopoulos, J., Deryng, D., Folberth, C., Pugh, T. A., and Schmid, E.: Implications of climate mitigation for future agricultural production, *Environmental Research Letters*, 10, 125 004, 2015.
- Müller, C., Elliott, J., Chryssanthacopoulos, J., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., Folberth, C., Glotter, M., Hoek, S., Iizumi, T., Izaurralde, R. C., Jones, C., Khabarov, N., Lawrence, P., Liu, W., Olin, S., Pugh, T. A. M., Ray, D. K., Reddy, A., Rosenzweig, C., Ruane, A. C., Sakurai, G., Schmid, E., Skalsky, R., Song, C. X., Wang, X., de Wit, A., and Yang, H.: Global gridded crop model evaluation: 480 benchmarking, skills, deficiencies and implications, *Geoscientific Model Development*, 10, 1403–1422, <https://doi.org/10.5194/gmd-10-1403-2017>, 2017.
- Olin, S., Schurgers, G., Lindeskog, M., Wårldin, D., Smith, B., Bodin, P., Holmér, J., and Arneth, A.: Modelling the response of yields and tissue C:N to changes in atmospheric CO₂ and N management in the main wheat regions of western Europe, *Biogeosciences*, 12, 2489–2515, <https://doi.org/10.5194/bg-12-2489-2015>, 2015.
- 485 Osborne, T., Gornall, J., Hooker, J., Williams, K., Wiltshire, A., Betts, R., and Wheeler, T.: JULES-crop: a parametrisation of crops in the Joint UK Land Environment Simulator, *Geoscientific Model Development*, 8, 1139–1155, <https://doi.org/10.5194/gmd-8-1139-2015>, 2015.
- Pirttioja, N., Carter, T., Fronzek, S., Bindi, M., Hoffmann, H., Palosuo, T., Ruiz-Ramos, M., Tao, F., Trnka, M., Acutis, M., Asseng, S., Baranowski, P., Basso, B., Bodin, P., Buis, S., Cammarano, D., Deligios, P., Destain, M., Dumont, B., Ewert, F., Ferrise, R., François, L., Gaiser, 490 T., Hlavinka, P., Jacquemin, I., Kersebaum, K., Kollas, C., Krzyszczak, J., Lorite, I., Minet, J., Minguez, M., Montesino, M., Moriondo, M., Müller, C., Nendel, C., Öztürk, I., Perego, A., Rodríguez, A., Ruane, A., Ruget, F., Sanna, M., Semenov, M., Slawinski, C., Stratonovitch, P., Supit, I., Waha, K., Wang, E., Wu, L., Zhao, Z., and Rötter, R.: Temperature and precipitation effects on wheat yield across a European transect: a crop model ensemble analysis using impact response surfaces, *Climate Research*, 65, 87–105, <https://doi.org/10.3354/cr01322>, 2015.
- 495 Porter et al. (IPCC): Food security and food production systems. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, in: *IPCC Fifth Assessment Report*, edited by et al., C. F., pp. 485–533, Cambridge University Press, Cambridge, UK, 2014.
- Portmann, F., Siebert, S., and Doell, P.: MIRCA2000 - Global Monthly Irrigated and Rainfed Crop Areas around the Year 2000: 500 A New High-Resolution Data Set for Agricultural and Hydrological Modeling, *Global Biogeochemical Cycles*, 24, GB1011, <https://doi.org/10.1029/2008GB003435>, 2010.
- Porwollik, V., Müller, C., Elliott, J., Chryssanthacopoulos, J., Iizumi, T., Ray, D. K., Ruane, A. C., Arneth, A., Balkovič, J., Ciais, P., Deryng, D., Folberth, C., Izaurralde, R. C., Jones, C. D., Khabarov, N., Lawrence, P. J., Liu, W., Pugh, T. A., Reddy, A., Sakurai, G., Schmid, E., Wang, X., de Wit, A., and Wu, X.: Spatial and temporal uncertainty of crop yield aggregations, *European Journal of Agronomy*, 88, 10–21, <https://doi.org/10.1016/j.eja.2016.08.006>, 2017.
- 505 Pugh, T., Müller, C., Elliott, J., Deryng, D., Folberth, C., Olin, S., Schmid, E., and Arneth, A.: Climate analogues suggest limited potential for intensification of production on current croplands under climate change, *Nature Communications*, 7, 12 608, <https://doi.org/10.1038/ncomms12608>, 2016.
- Ray, D., Ramankutty, N., Mueller, N., West, P., and A Foley, J.: Recent patterns of crop yield growth and stagnation, *Nature communications*, 3, 1293, <https://doi.org/10.1038/ncomms2296>, 2012.

- 510 Roberts, M., Braun, N., R Sinclair, T., B Lobell, D., and Schlenker, W.: Comparing and combining process-based crop models and statistical models with some implications for climate change, *Environmental Research Letters*, 12, <https://doi.org/10.1088/1748-9326/aa7f33>., 2017.
- Rosenzweig, C., Jones, J., Hatfield, J., Ruane, A., Boote, K., Thorburn, P., Antle, J., Nelson, G., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G., and Winter, J.: The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies, *Agricultural and Forest Meteorology*, 170, 166 – 182, <https://doi.org/10.1016/j.agrformet.2012.09.011>, 2013.
- 515 Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., Boote, K. J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T. A. M., Schmid, E., Stehfest, E., Yang, H., and Jones, J. W.: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison, *Proceedings of the National Academy of Sciences*, 111, 3268–3273, <https://doi.org/10.1073/pnas.1222463110>, 2014.
- Rosenzweig, C., Ruane, A. C., Antle, J., Elliott, J., Ashfaq, M., Chatta, A. A., Ewert, F., Folberth, C., Hathie, I., Havlik, P., Hoogenboom, G., Lotze-Campen, H., MacCarthy, D. S., Mason-D'Croz, D., Contreras, E. M., Müller, C., Perez-Dominguez, I., Phillips, M., Porter, C., Raymundo, R. M., Sands, R. D., Schleussner, C.-F., Valdivia, R. O., Valin, H., and Wiebe, K.: Coordinating AgMIP data and models across global and regional scales for 1.5°C and 2.0°C assessments, *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 376, <https://doi.org/10.1098/rsta.2016.0455>, 2018.
- Rötter, R. P., Carter, T. R., Olesen, J. E., and Porter, J. R.: Crop-climate models need an overhaul, *Nature climate change*, 1, 175, 2011.
- 520 Ruane, A. C., McDermid, S., Rosenzweig, C., Baigorria, G. A., Jones, J. W., Romero, C. C., and Cecil, L. D.: Carbon-temperature-water change analysis for peanut production under climate change: A prototype for the AgMIP Coordinated Climate-Crop Modeling Project (C3MP), *Glob. Change Biology*, 20, 394–407, <https://doi.org/10.1111/gcb.12412>, 2014.
- Ruane, A. C., Goldberg, R., and Chryssanthacopoulos, J.: Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation, *Agric. Forest Meteorol.*, 200, 233–248, <https://doi.org/10.1016/j.agrformet.2014.09.016>, 2015.
- 530 Ruane, A. C., Antle, J., Elliott, J., Folberth, C., Hoogenboom, G., Mason-D'Croz, D., Müller, C., Porter, C., Phillips, M. M., Raymundo, R. M., Sands, R., Valdivia, R. O., White, J. W., Wiebe, K., and Rosenzweig, C.: Biophysical and economic implications for agriculture of +1.5° and +2.0°C global warming using AgMIP Coordinated Global and Regional Assessments, *Climate Research*, 76, 17–39, <https://doi.org/10.3354/cr01520>, 2018.
- Rubel, F. and Kottek, M.: Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification, *Meteorologische Zeitschrift*, 19, 135–141, <https://doi.org/10.1127/0941-2948/2010/0430>, 2010.
- Ruiz-Ramos, M., Ferrise, R., Rodríguez, A., Lorite, I., Bindl, M., Carter, T., Fronzek, S., Palosuo, T., Pirttioja, N., Baranowski, P., Buis, S., Cammarano, D., Chen, Y., Dumont, B., Ewert, F., Gaiser, T., Hlavinka, P., Hoffmann, H., Höhn, J., Jurecka, F., Kersebaum, K., Krzyszczak, J., Lana, M., Mechiche-Alami, A., Minet, J., Montesino, M., Nendel, C., Porter, J., Ruget, F., Semenov, M., Steinmetz, Z., Strattonovitch, P., Supit, I., Tao, F., Trnka, M., de Wit, A., and Rötter, R.: Adaptation response surfaces for managing wheat under perturbed climate and CO₂ in a Mediterranean environment, *Agricultural Systems*, 159, 260 – 274, <https://doi.org/10.1016/j.agsy.2017.01.009>, 2018.
- Sacks, W. J., Deryng, D., Foley, J. A., and Ramankutty, N.: Crop planting dates: an analysis of global patterns, *Global Ecology and Biogeography*, 19, 607–620, <https://doi.org/10.1029/2009GB003765>, 2010.
- Schauberger, B., Archontoulis, S., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., Elliott, J., Folberth, C., Khabarov, N., Müller, C., A. M. Pugh, T., Rolinski, S., Schaphoff, S., Schmid, E., Wang, X., Schlenker, W., and Frieler, K.: Consistent negative response of US crops to high temperatures in observations and crop models, *Nature Communications*, 8, 13 931, <https://doi.org/10.1038/ncomms13931>, 2017.

- Schewe, J., Gosling, S. N., Reyer, C., Zhao, F., Ciais, P., Elliott, J., Francois, L., Huber, V., Lotze, H. K., Seneviratne, S. I., van Vliet, M. T. H., Vautard, R., Wada, Y., Breuer, L., Büchner, M., Carozza, D. A., Chang, J., Coll, M., Deryng, D., de Wit, A., Eddy, T. D., Folberth, C., Frieler, K., Friend, A. D., Gerten, D., Gudmundsson, L., Hanasaki, N., Ito, A., Khabarov, N., Kim, H., Lawrence, P., Morfopoulos, C., Müller, C., Müller Schmied, H., Orth, R., Ostberg, S., Pokhrel, Y., Pugh, T. A. M., Sakurai, G., Satoh, Y., Schmid, E., Stacke, T., Steenbeek, J., Steinkamp, J., Tang, Q., Tian, H., Tittensor, D. P., Volkholz, J., Wang, X., and Warszawski, L.: State-of-the-art global models underestimate impacts from climate extremes, *Nature Communications*, 10, 1005–, <https://doi.org/10.1038/s41467-019-08745-6>, 2019.
- Snyder, A., Calvin, K. V., Phillips, M., and Ruane, A. C.: A crop yield change emulator for use in GCAM and similar models: Persephone v1.0, Accepted for publication in *Geoscientific Model Development*, pp. 1–42, <https://doi.org/10.5194/gmd-2018-195>, in open review, 2018.
- Stevanović, M., Popp, A., Lotze-Campen, H., Dietrich, J. P., Müller, C., Bonsch, M., Schmitz, C., Bodirsky, B. L., Humpenöder, F., and Weindl, I.: The impact of high-end climate change on agricultural welfare, *Science Advances*, 2, <https://doi.org/10.1126/sciadv.1501452>, <https://advances.sciencemag.org/content/2/8/e1501452>, 2016.
- Vadez, V., Berger, J. D., Warkentin, T., Asseng, S., Ratnakumar, P., Rao, K. P. C., Gaur, P. M., Munier-Jolain, N., Larmure, A., Voisin, A.-S., et al.: Adaptation of grain legumes to climate change: a review, *Agronomy for Sustainable Development*, 32, 31–44, 2012.
- von Bloh, W., Schaphoff, S., Müller, C., Rolinski, S., Waha, K., and Zaehle, S.: Implementing the Nitrogen cycle into the dynamic global vegetation, hydrology and crop growth model LPJmL (version 5.0), *Geoscientific Model Development*, 11, 2789–2812, <https://doi.org/10.5194/gmd-11-2789-2018>, 2018.
- Waha, K., Van Bussel, L., Müller, C., and Bondeau, A.: Climate-driven simulation of global crop sowing dates, *Global Ecology and Biogeography*, 21, 247–259, 2012.
- Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J., and Viterbo, P.: The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data, *Water Resources Research*, 50, 7505–7514, 2014.
- Wheeler, T. and Von Braun, J.: Climate change impacts on global food security, *Science*, 341, 508–513, 2013.
- Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., van der Mensbrugghe, D., Biewald, A., Bodirsky, B., Islam, S., Kavallari, A., Mason-D'Croz, D., Müller, C., Popp, A., Robertson, R., Robinson, S., van Meijl, H., and Willenbockel, D.: Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios, *Environmental Research Letters*, 10, 085010, <https://doi.org/10.1088/1748-9326/10/8/085010>, <https://doi.org/10.1088%2F1748-9326%2F10%2F8%2F085010>, 2015.
- Williams, K., Gornall, J., Harper, A., Wiltshire, A., Hemming, D., Quaife, T., Arkebauer, T., and Scoby, D.: Evaluation of JULES-crop performance against site observations of irrigated maize from Mead, Nebraska, *Geoscientific Model Development*, 10, 1291–1320, <https://doi.org/10.5194/gmd-10-1291-2017>, 2017.
- Williams, K. E. and Falloon, P. D.: Sources of interannual yield variability in JULES-crop and implications for forcing with seasonal weather forecasts, *Geoscientific Model Development*, 8, 3987–3997, <https://doi.org/10.5194/gmd-8-3987-2015>, 2015.
- Wolf, J. and Oijen, M.: Modelling the dependence of European potato yields on changes in climate and CO₂, *Agricultural and Forest Meteorology*, 112, 217 – 231, [https://doi.org/10.1016/S0168-1923\(02\)00061-8](https://doi.org/10.1016/S0168-1923(02)00061-8), 2002.
- Wu, X., Vuichard, N., Ciais, P., Viovy, N., de Noblet-Ducoudré, N., Wang, X., Magliulo, V., Wattenbach, M., Vitale, L., Di Tommasi, P., Moors, E. J., Jans, W., Elbers, J., Ceschia, E., Tallec, T., Bernhofer, C., Grünwald, T., Moureaux, C., Manise, T., Ligne, A., Cellier, P., Loubet, B., Larmanou, E., and Ripoche, D.: ORCHIDEE-CROP (v0), a new process-based agro-land surface model: model description and evaluation over Europe, *Geoscientific Model Development*, 9, 857–873, <https://doi.org/10.5194/gmd-9-857-2016>, 2016.

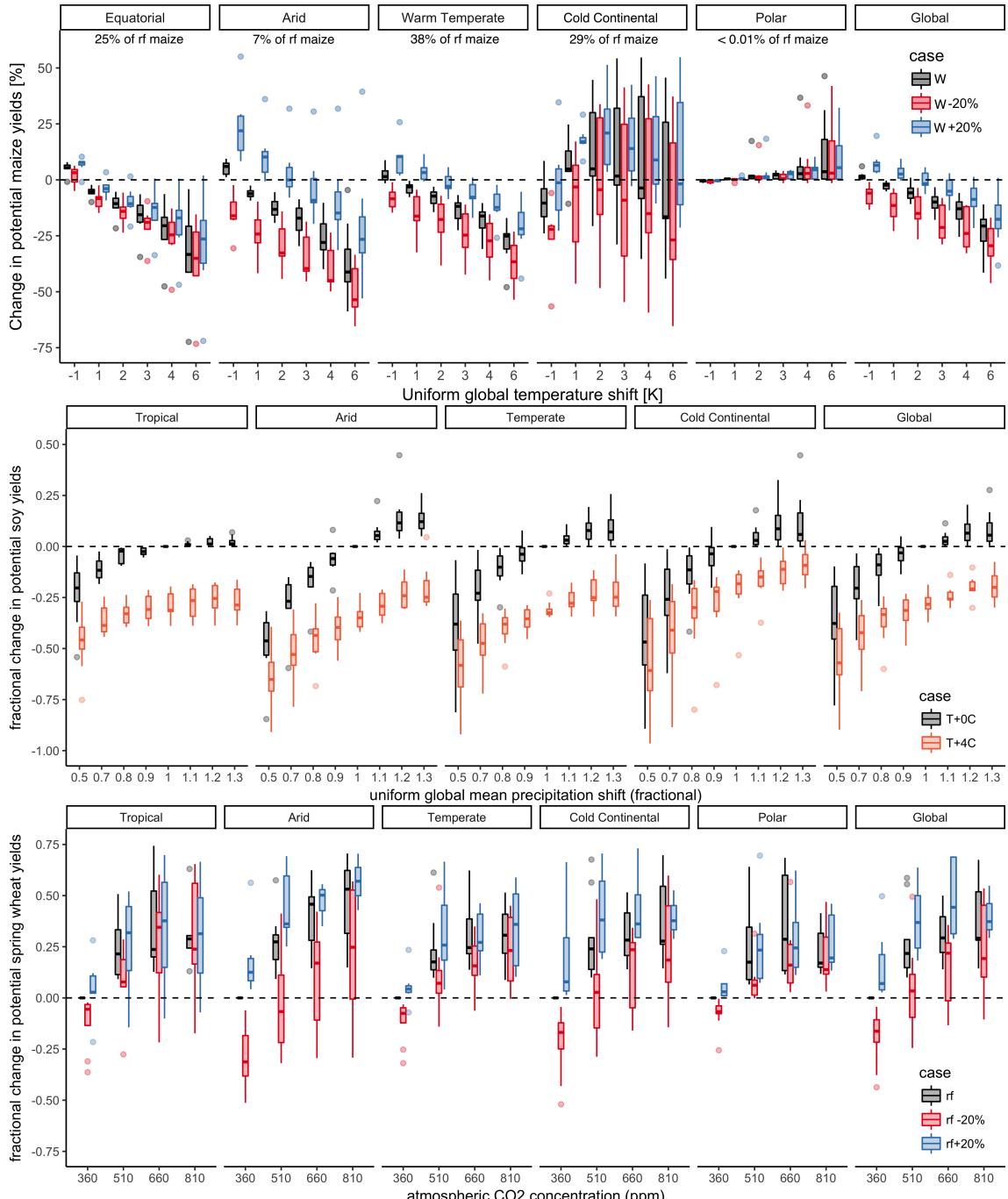


Figure 5. Illustration of the distribution of regional yield changes across the multi-model ensemble, split by Köppen-Geiger climate regions (?). We show responses of a single crop (rainfed maize) to applied uniform temperature perturbations, for three discrete precipitation perturbation levels (-20%, 0%, and +20%), with [CO₂] and nitrogen held constant at baseline values (360 pmm and 200 kg ha⁻¹ yr⁻¹). Y-axis is fractional change in the regional average climatological potential yield relative to the baseline. Box-and-whiskers plots show distribution across models, with median marked; edges are first and third quartiles, i.e. box height is the interquartile range (IQR). If all models like within 1.5·IQR then whiskers extend to maximum and minimum of simulations, else the outlier is shown separately. Outliers in the tropics (strong negative impact of temperature increases) are the pDSSAT model; outliers in the high-rainfall case (strong positive impact of precipitation increases) are the JULES model. Figure shows all modeled land area; see Figure S4 in the supplemental material for currently-cultivated