Supporting Information for "Global response patterns of major rainfed crops to adaptation by maintaining current growing periods and irrigation"

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Introduction

S1. GGCMI phase 2 CTWN-A protocol

The overall scientific rationale of the GGCMI phase 2 protocol (`https://agmip.org/protocolsandreports/`) is to conduct a comparative analysis of the strategies and mechanisms used in different models to describe Carbon, Temperature, Water, Nitrogen and Adaptation (CTWN-A) processes, interactions, and feedbacks. This analysis framework builds on the AgMIP Coordinated Climate-Crop Modeling Project (Ruane et al., 2013; McDermid et al., 2015) efforts to compare models, sites, and uncertainty, and extends the concept now to global gridded simulations. This also provides a basis for comparison between grids and site-based networks. Moreover, it aims at enhanced understanding of how models work, characterizing models by sensitivity to drivers, and assesses aggregated model responses at different aggregation levels (e.g. Köppen-Geiger climate zones).

GGCMI participants run models globally using harmonized input data. The AgMERRA climate data set from 1980-2010 is used as in phase 1 (Elliott et al., 2015). Groups that require data on long-wave radiation are asked to use the data from the Princeton GF (version 1, not PGFv2). Nitrogen and CO_2 are specified at globally uniform levels and are not provided as spatially explicit data sets. Nitrogen fertilizer is to be applied in 2 doses, 50% at planting and 50% at a crop- and pixel specific date (40 days after planting for all spring crops, case-specific for winter wheat). All other sources of nitrogen supply (mineralization, fixation by soy) have to be reported in the outputs, no deposition or soil-only fixation should be applied. Modelers are asked to find implement themselves scenarios of CTWN offsets.

Four levels of participation are defined (*low, mid, high, super tier*). GGCM crop-specific output variables of highest priority have to be submitted per growing season: yield (t DM ha^{-1} yr^{-1}); total above ground biomass yield (t DM ha^{-1} yr^{-1}); actual planting date (day of year); anthesis date (day of year), maturity date (days from planting); applied irrigation water (mm yr^{-1}), evapotranspiration (growing season sum, mm yr^{-1}).

To reduce the computational burden, regions that are considered unsuitable are cut out of the simulation. Unsuitable areas are defined according to global Agro-ecological Zones (GAEZ, Fischer et al., 2012). There are a few cases, where (at the resolution of 0.5 degrees) according to GAEZ, the pixels is classified as dominantly unsuitable, but the cropland masks (MIRCA2000) assign cropland to these pixels. To ensure that all cropland currently used in the aggregation is also simulated by the groups, only pixels that are predominantly unsuitable ($\geq$ 90%) and do not contain any cropland (according to MIRCA2000) are excluded. By excluding the so defined unsuitable land, simulation results (all crops everywhere) can be aggregated by any land-use pattern in subsequent analyses.

S2. Model characteristics and protocol implementation details

S2.1. CARAIB

CARAIB simulates the crop development from sowing to harvest, requiring a certain (crop-specific) heat accumulation to be reached. A cultivar is attributed to each grid cell as a function of the cell growing season temperature and soil water availability (see below). To germinate a crop needs to accumulate some temperature and soil water conditions must also be suitable for seed germination, so that some delay can occur between sowing and germination. For instance, with a base temperature of 0°C, wheat germinates when

GDD0 = 140°Cd and only if soil water conditions are suitable. Wheat reaches maturity when GDD0 attains at least 1800°Cd but some cultivars require more (up to 4000°Cd). In the model, stress occurs under critical soil water content and (minimum) temperature. CARAIB considers crop stress on growth processes from cold temperatures below 0, 8, 7, 0, -2 °C for maize, rice, soybean, spring wheat, winter wheat respectively. If temperature is lower than crop tolerance, the crop biomass is impacted but plant is not necessarily killed. In this case, crop can reach maturity but with insignificant yield.

CARAIB follows a modified protocol with harmonized sowing dates, while the model was not calibrated to match observed maturity dates of each grid cell. The simulated growing season of a crop is constrained by observed cropping calendars. Specifically, Sacks et al. (2010) is used to define the crop-specific maximum growing season length. For instance, if wheat does not reach maturity within 200 days, it is not harvested. Minimum and maximum GDD sums (extreme cultivars) are derived from observed growing period lengths, reported for each crop by Sacks et al. (2010). Between these extreme cultivars, there are a series of intermediate cultivars. A cultivar is attributed to each grid cell as a function of the cell temperature over the growing period (temperature accumulation) with soil water availability limiting the growing period length. The new-cultivar adaptation measure was implemented based on the partially-harmonized growing period length obtained under the baseline temperature scenario (T0). Adaptation was based on temperature only, while water limitations were kept constant under the rainfed as well as the irrigated scenarios.

S2.2. GEPIC

GEPIC simulates the phenological development rate as null below T_{min}, equal to $T_{day} - T_{min}$ between T_{min} and T_{opt}, and maximum at T_{opt}. To harmonize the growing periods growing degree days only were tuned. Default parameters from EPICv0810 for T_{min} and T_{opt} were used. T_{min} and T_{opt} together with long-term (1980-2010) monthly climate data were used to calculate the average GDD in each pixel based on reported harvest and planting dates. GEPIC provided simulation results for a subset of T levels. The output variables of the missing levels (either T1 & T3, or T2) were derived by linear interpolation.

S2.3. LPJ-GUESS

LPJ-GUESS simulates the phenological development rate as null below T_{min} and above T_{max}, and maximum at T_{opt}. To harmonize the growing period GDD to maturity only were tuned. The GDD sum to maturity was calculated automatically in the no-adaptation T0 simulation based on a 10-year running mean of GDD sum over a default growing period (Lindeskog et al., 2013). The resulting annual GDD sums over 1980-2010 were read in as external forcing for all no-adaptation simulations under perturbed temperature. Simulations with growing period adaptation adjusted GDD sum to maturity based on the above running mean method throughout the simulation. LPJ-GUESS provided simulation results for a subset of crops: maize, spring wheat, winter wheat.

S2.4. LPJmL

LPJmL simulates the phenological development rate as null below T_{min}, otherwise it is $T_{day} - T_{min}$. To harmonize the growing periods GDD only were tuned. Simulations with increased GDD requirements were conducted, so that crops would grow beyond the prescribed harvest day and recorded the GDD accumulated on that day. For the CTWN-

A simulations, the recorded GDD on the harvest day was averaged over the AgMERRA time period and prescribed per pixel and crop. Prescribed sowing dates are exactly met, prescribed maturity dates are met on average. Vernalization in winter wheat made GDD pre-computation more complicated and maturity dates may be less accurate there.

S2.5. pDSSAT

pDSSAT simulates phenological development rate as null below T_{min} and maximum at T_{opt}. Different T_{opt} values are defined for vegetative and reproductive stages. Phenological phases for maize and rice are defined as time from sowing-to-anthesis and from anthesis-to-maturity. For soy the following phases are defined: EM-FL, Time between plant emergence and flower appearance (R1) (photothermal days); FL-SH, Time between first flower and first pod (R3) (photothermal days) FL-SD, Time between first flower and first seed (R5) (photothermal days) FL-LF, Time between first flower (R1) and end of leaf expansion (photothermal days) SD-PM, Time between first seed (R5) and physiological maturity (R7) (photothermal days). For wheat the following phases are defined: P1, Duration of phase end juvenile to terminal spikelet (PVTU) P2, Duration of phase terminal spikelet to end leaf growth (TU) P2FR1, Duration of phase terminal spikelet to jointing (fr P2) P3, Duration of phase end leaf growth to end spike growth (TU) P4, Duration of phase end spike growth to end grain fill lag (TU) P4FR1, Duration of phase end spike growth to anthesis (fr P4) P4FR2, Duration of phase anthesis start to anthesis end (fr P4) P5, Grain filling (excluding lag) phase duration (°Cd).

S2.6. PEPIC

PEPIC simulates the phenological development rate as null below T_{min} and maximum at T_{opt} (default values of the EPIC model). To harmonize the growing periods GDD only were tuned. PEPIC provided simulation results for a subset of T levels. The output variables of the missing levels (either T1 & T3, or T2) were derived by linear interpolation.

S2.7. PROMET

To simulate the crop phenological progress, the applied version of PROMET (v7) uses a curvilinear (bell-shaped) temperature response function of crop development rate. Three parameters (T_{min}, T_{opt}, T_{max}) are used for calibrating the function: the rate is null below T_{min} and above T_{max}, and is maximum at T_{opt}. In addition, vernalization and light effect potentially inhibit phenological progress. Water stress is considered indirectly via the leaf temperature. PROMET uses leaf temperature, which leads to different phenology between rainfed and irrigated crops and all W-dimensions, because reduced water supply results in increased leaf temperatures that usually accelerates phenological development, but could also decrease phenological development rates, if temperature is already beyond the cardinal temperature of T_{opt}. In addition to drought mortality, PROMET considers temperature mortality (due to heat or extreme frost events). Besides phenological development and photosynthesis rates, heat stress impacts on leaf temperature and thus on stomatal conductance and transpiration and thus feed backs to development and photosynthesis. With exception of the phenological impacts, none of these effects are permanent. Leaf color and thus PAR (photosynthetic active radiation) is affected by an increase in brown leaf pigments, but only during senescence. Browning of leaves during short-term heat events in not considered. To harmonize the growing periods, sowing dates were prescribed from the given data set and the model harvest dates were pre-calculated. The offset between simulated harvest dates and given harvest dates were used to calibrate a phenological acceleration/retardation factor. Then the model was run again, this time matching the given dates for sowing and harvest. On some grid cells, the pre-calculation did not succeed, e.g. due to crop failure. In this case, no phenological acceleration/retardation factor could be calculated. These grid cells were masked out and yield is set to NA. PROMET is applied at hourly simulation time step. The 3-hourly ERA-I data is temporally interpoltated to hourly data. PROMET outputs report yield failures as NA.

Table S1. GGCM phenology parametrization. T_{min}, T_{opt}, T_{max} are respectively the minimum, the optimum and the maximum cardinal temperatures of the phenological development response function to temperature. GDD_{min} and GDD_{max} are the minimum and maximum of the growing degree days range used by the GGCMs to calibrate thermal-time requirements. Parameters that are not included in the response function are indicated as NA. Non-reported values are left blank.

GGCM	Param.	maize	rice	soy	spring-wheat	winter-wheat
CARAIB	Tmin	8	8	7	0	0
	Topt	NA	NA	NA	NA	NA
	Tmax	NA	NA	NA	NA	NA
	GDDmin	1000	1000	1500	1800	2000
	GDDmax	3000	4000	3600	4000	4000
GEPIC	Tmin	8	10	10	5	0
	Topt	25	25	25	20	15
	Tmax	NA	NA	NA	NA	NA
	GDDmin	200	200	200	200	200
	GDDmax	4280	3728	3227	5291	6180
LPJ-GUESS	Tmin	8	NA	NA	0 - 8	0 - 8
	Topt	NA	NA	NA	24 - 29	24 - 29
	Tmax	NA	NA	NA	35 - 40	35 - 40
	GDDmin	100	NA	NA	100	100
	GDDmax	5059	NA	NA	5768	5791
LPJmL	Tmin	5	10	10	0	0
	Topt	NA	NA	NA	NA	NA
	Tmax	NA	NA	NA	NA	NA
	GDDmin	700	700	700	700	700
	GDDmax	unlimited	unlimited	unlimited	unlimited	unlimited
pDSSAT	Tmin	8	8			
	Topt					
	Tmax					
	GDDmin					
	GDDmax					
PEPIC	Tmin	8	10	10	5	0
	Topt	25	25	25	20	15
	Tmax	NA	NA	NA	NA	NA
	GDDmin	unlimited	unlimited	unlimited	unlimited	unlimited
	GDDmax	unlimited	unlimited	unlimited	unlimited	unlimited
PROMET	Tmin	8	12-15	15-17	0	0 - 8
	Topt	30	22-28	24-26	25	19-24
	Tmax	42	40	40	37	30-35
	GDDmin	NA	NA	NA	NA	NA
	GDDmax	NA	NA	NA	NA	NA

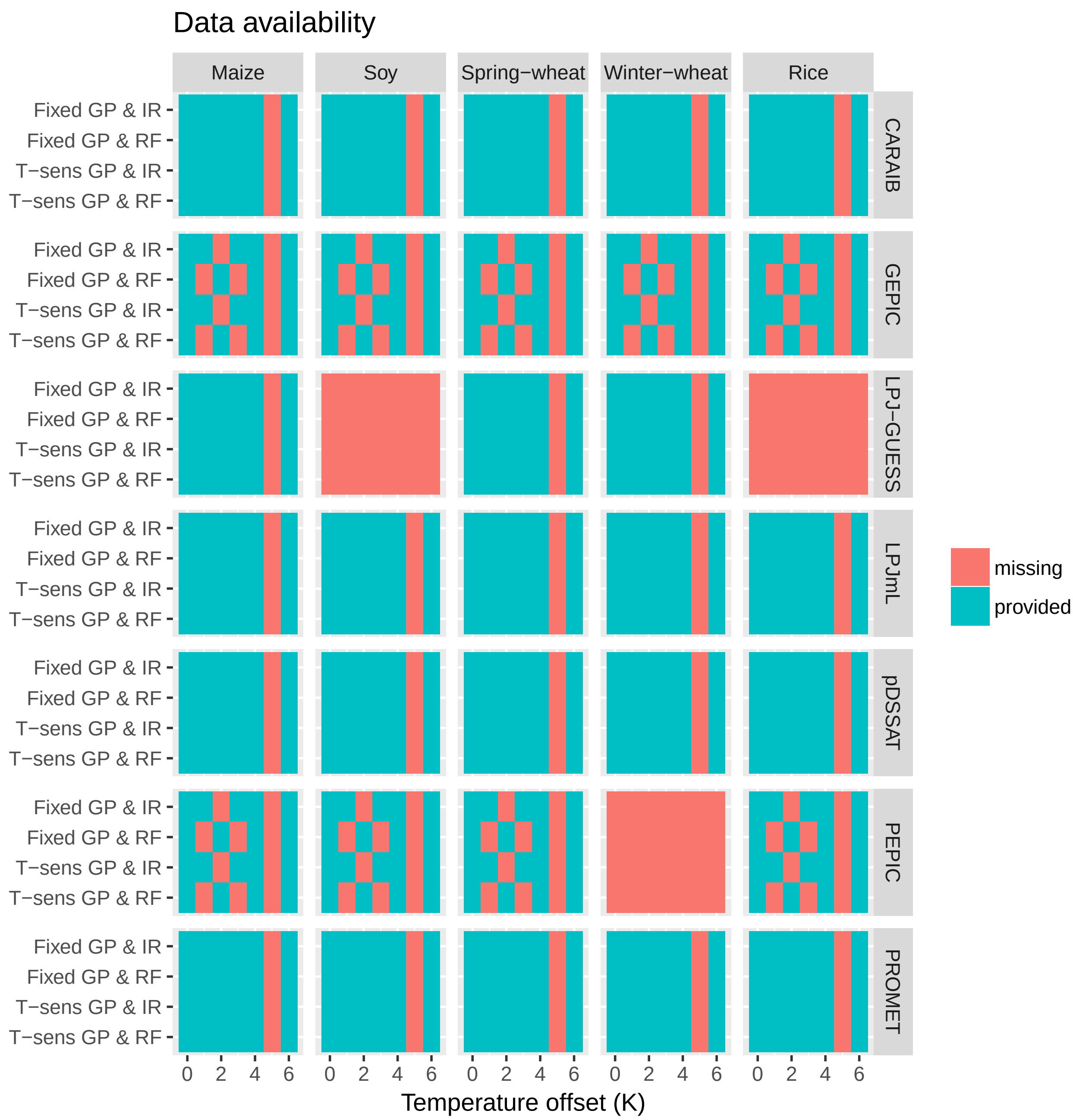

Figure S1. Available crop model simulations for each model, crop, temperature offset and management setting used in this study. Simulation setups missing (except for LPJ-GUESS rice, LPJ-GUESS soy, and PEPIC winter-wheat) are interpolated as described in Section 2.2.

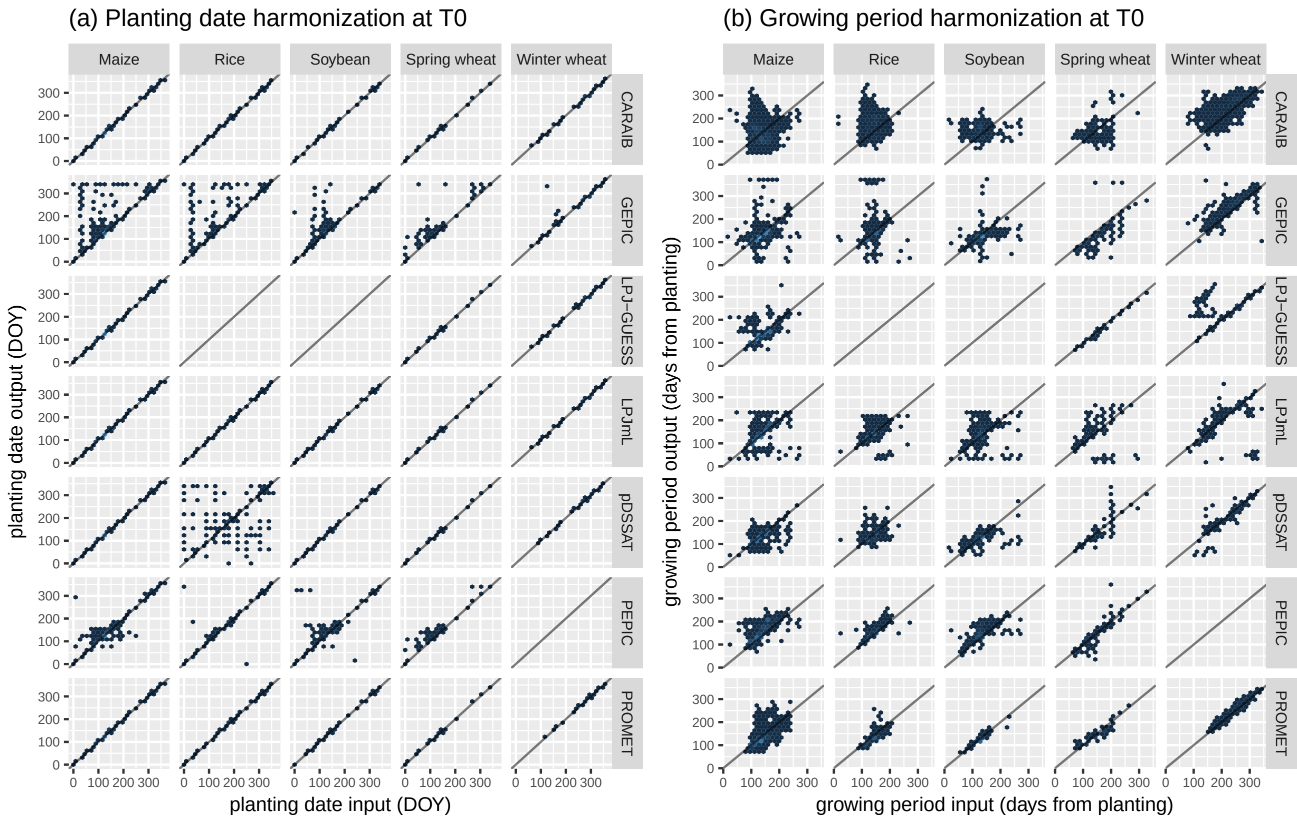

Figure S2. Evaluation of the growing period harmonization across GGCMs (T0, *historical management* setting). Prescribed planting (a) and maturity (b) dates are plotted against realized dated in each model (rows) and for each crop (column). The grey line is the 1:1 line. Across the model ensemble and crops, 94% of the cultivated cells have a modeled planting date within ±3 days compared to the prescribed dates. CARAIB, LPJ-GUESS, LPJmL and PROMET for instance meet these dates in all cells, while others like PEPIC, GEPIC or pDSSAT, have large systematic errors for some of the crops and do not meet these dates in up to 44% of the cells. Across the model ensemble and crops, only 40% of the cultivated cells have a modeled maturity date within ±3 days, and four models (CARAIB, PEPIC, PROMET, LPJmL) out of seven have maturity dates deviations larger than ±14 days from the observed in 22% or more of the cells.

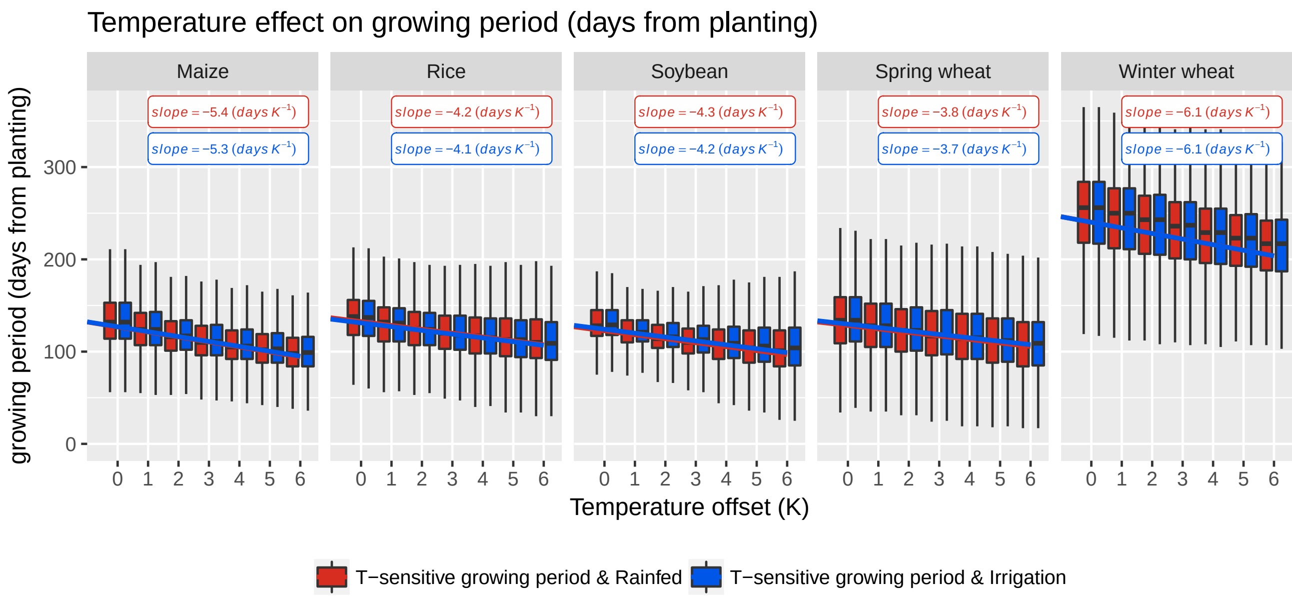

Figure S3. As Figure 2a but for both rainfed and irrigated crops.

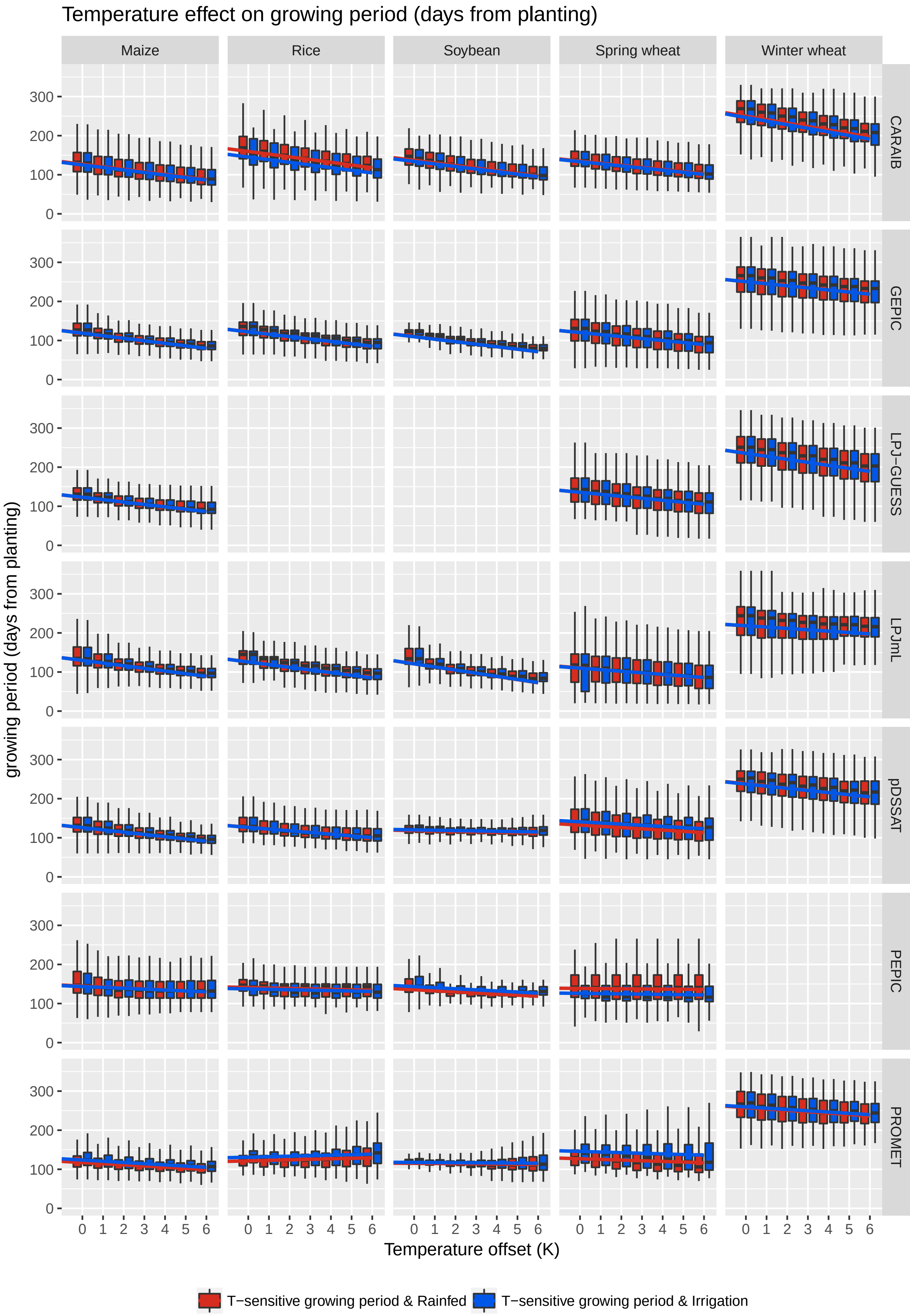

Figure S4. As Figure 2a but for both rainfed and irrigated crops for each GGCM.

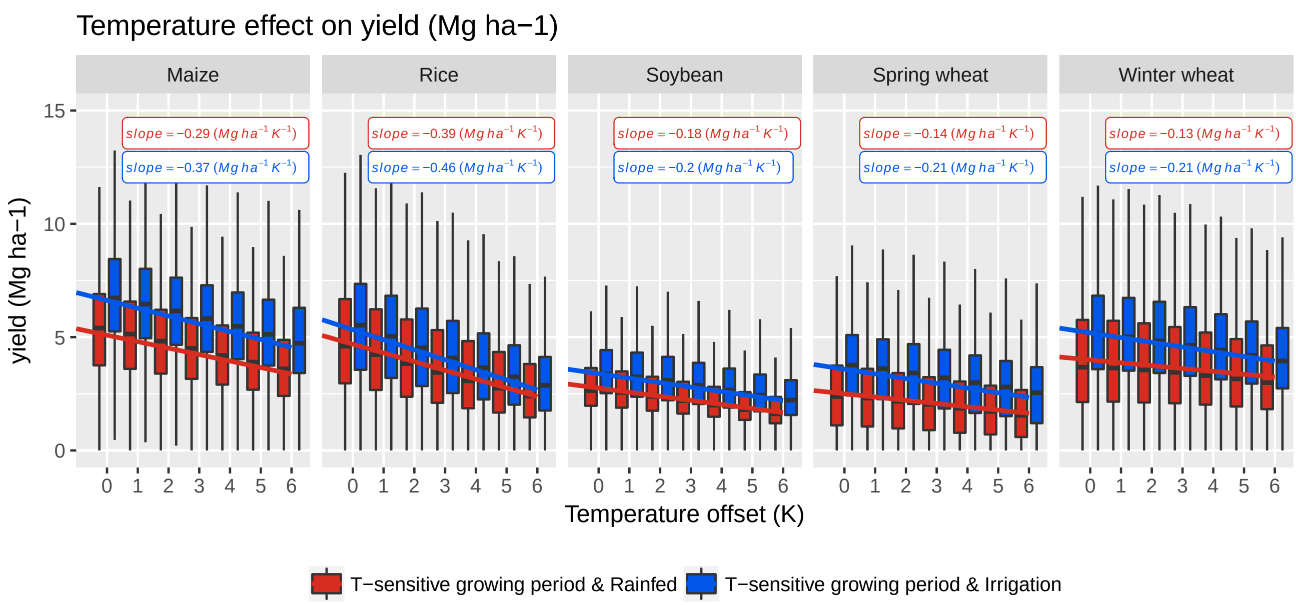

Figure S5. As Figure 2b but for both rainfed and irrigated crops.

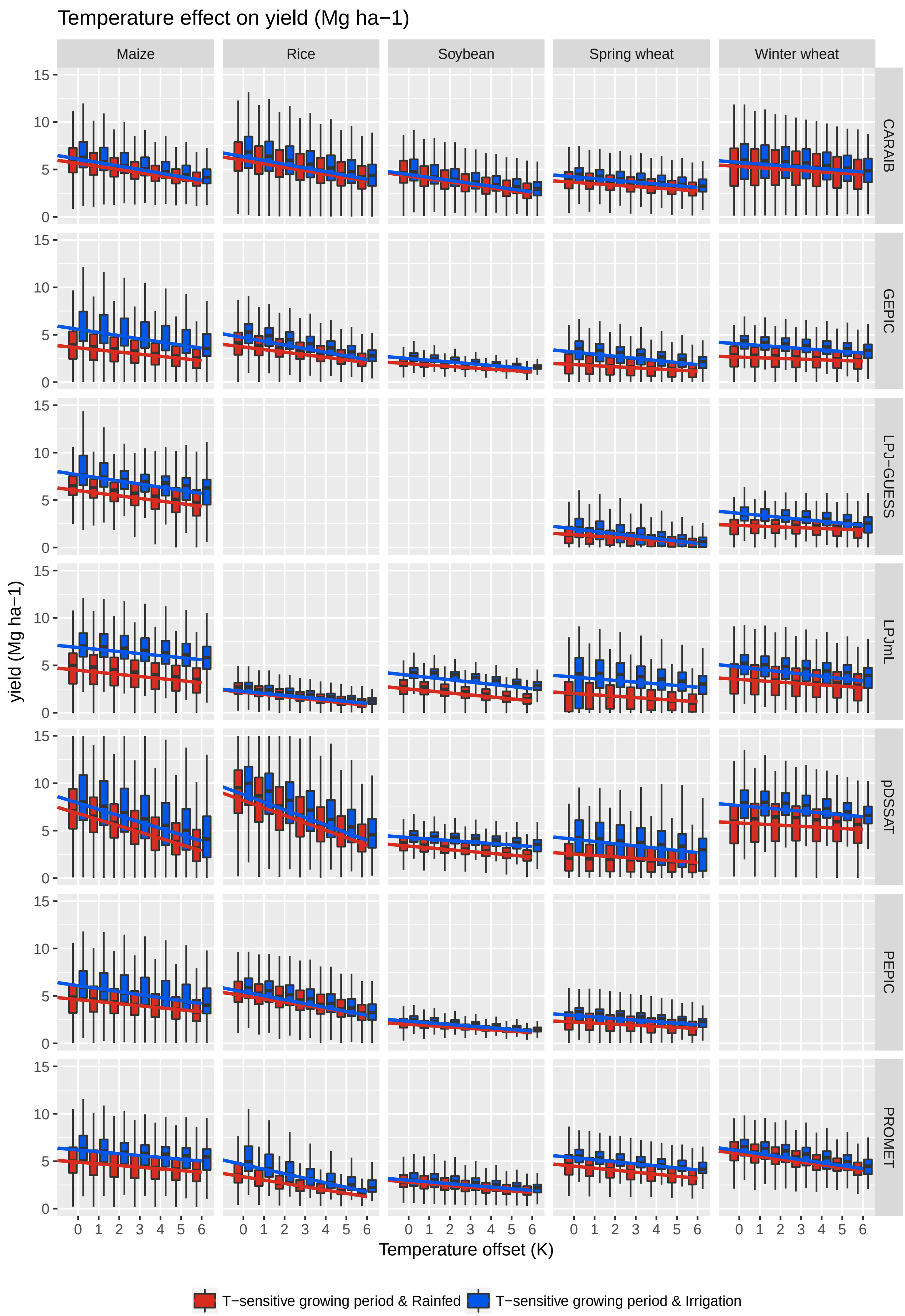

Figure S6. As Figure 2b but for both rainfed and irrigated crops for each GGCM.

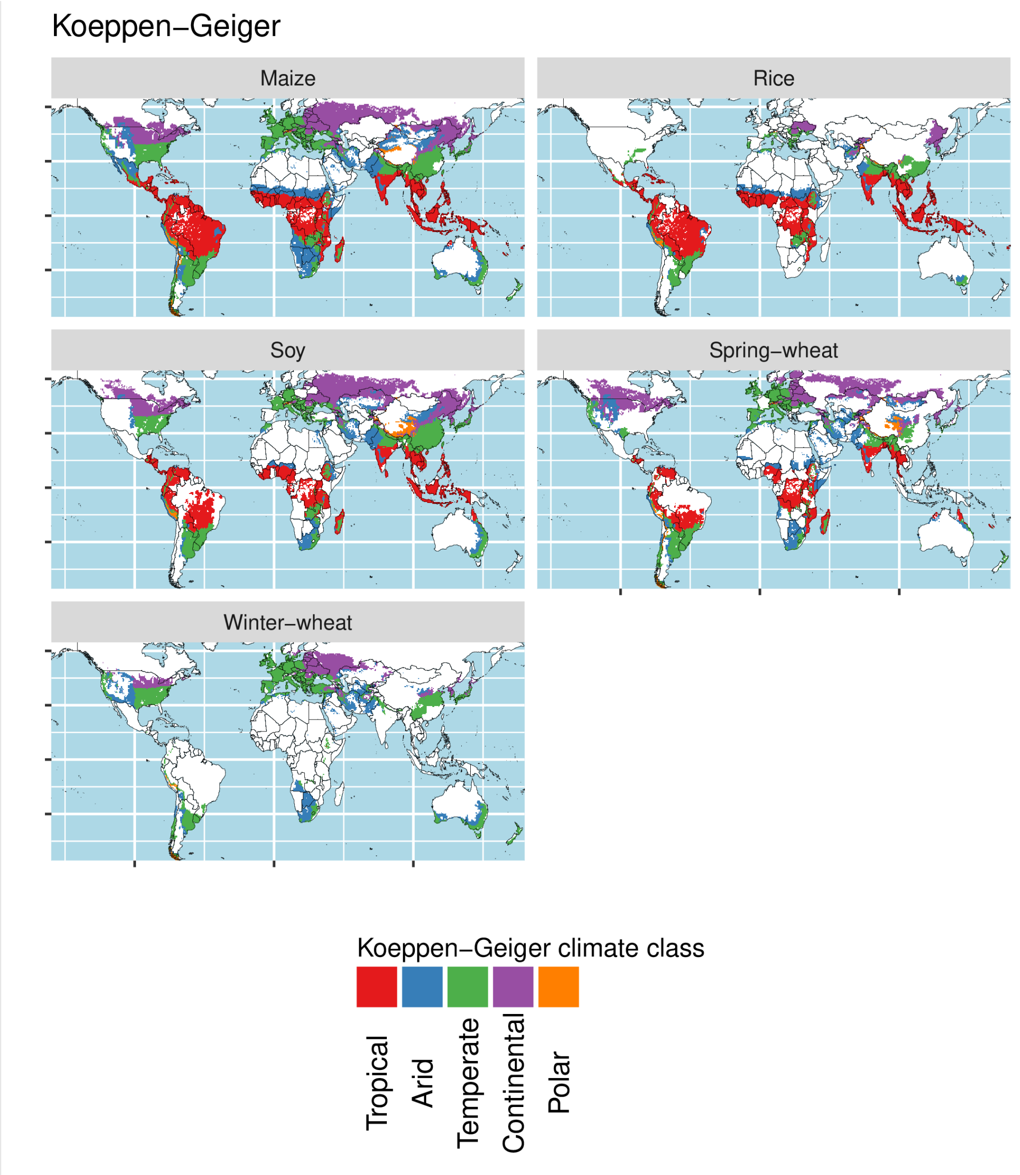

Figure S7. Cropland allocation in specific Koeppen-Geiger climate zones.

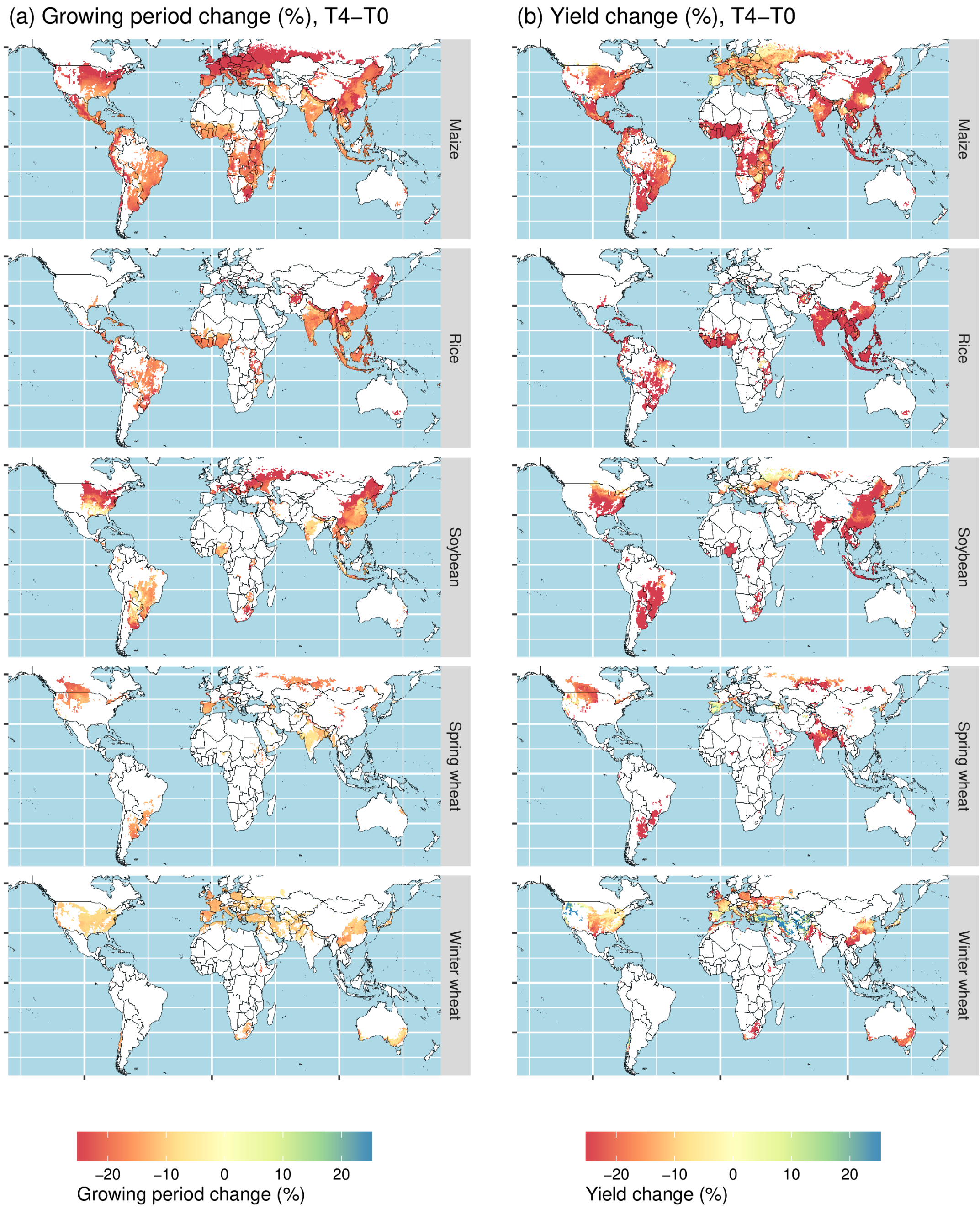

Figure S8. (a) Growing period change (%) and (b) yield change (%) with 4 K temperature increase. Each panel shows crop-specific ensemble median of the difference T4-T0 under static management ($CV_{old} + RF$).

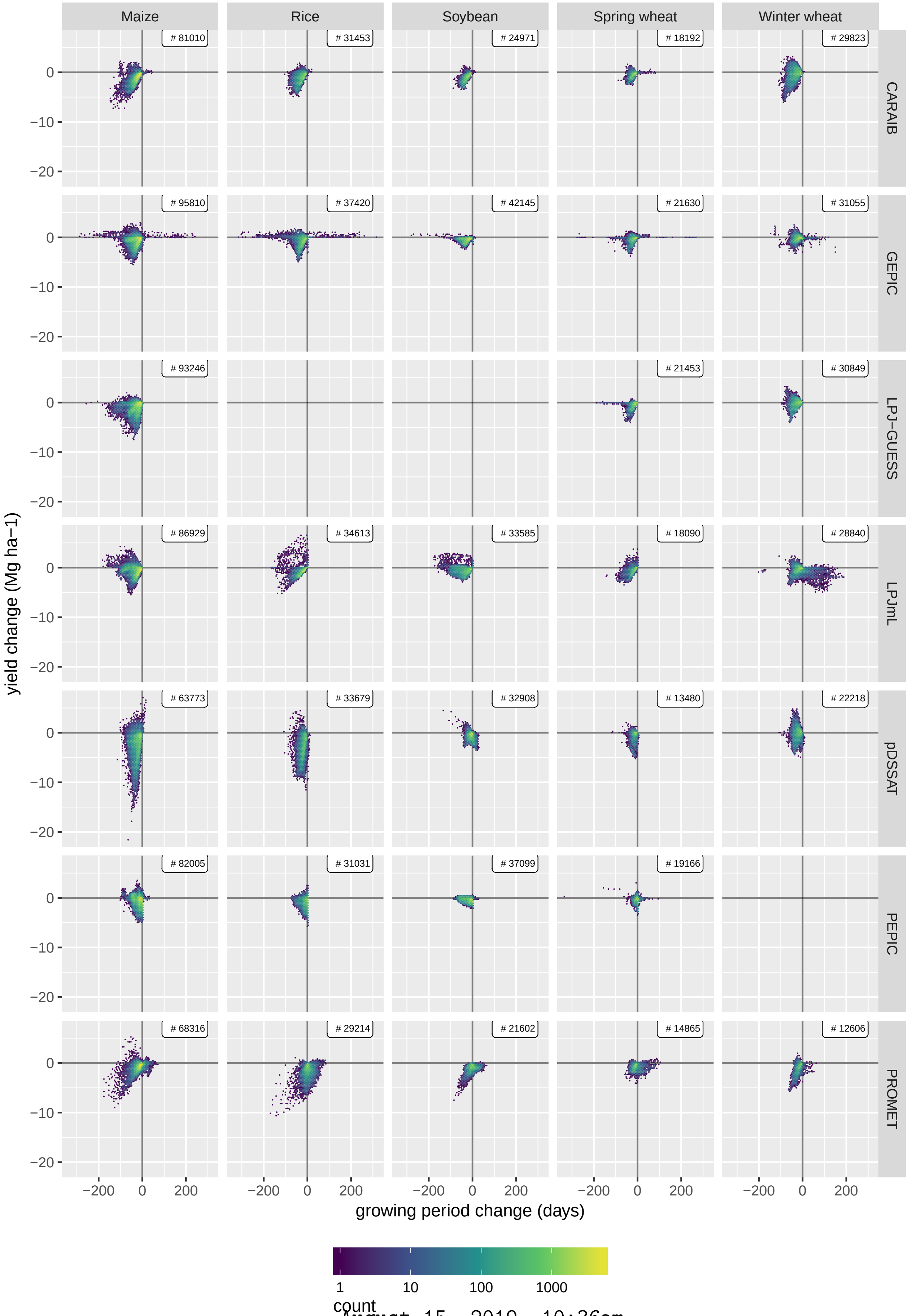

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Figure S9. As Figure 2c but for both rainfed and irrigated crops for each GGCM.

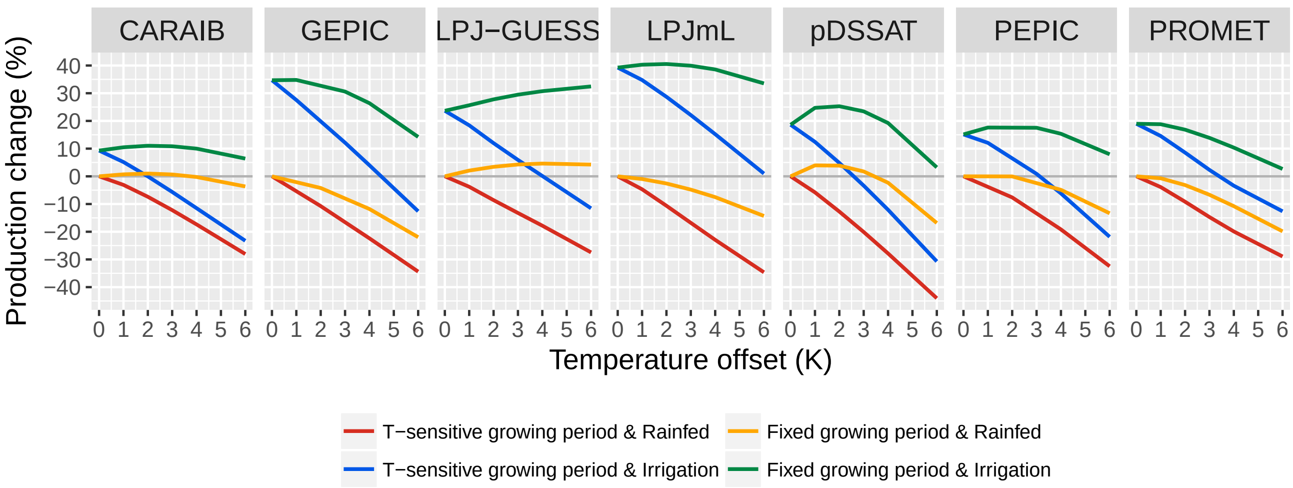

Figure S10. As Figure 3 (All crops), but for each GGCM.

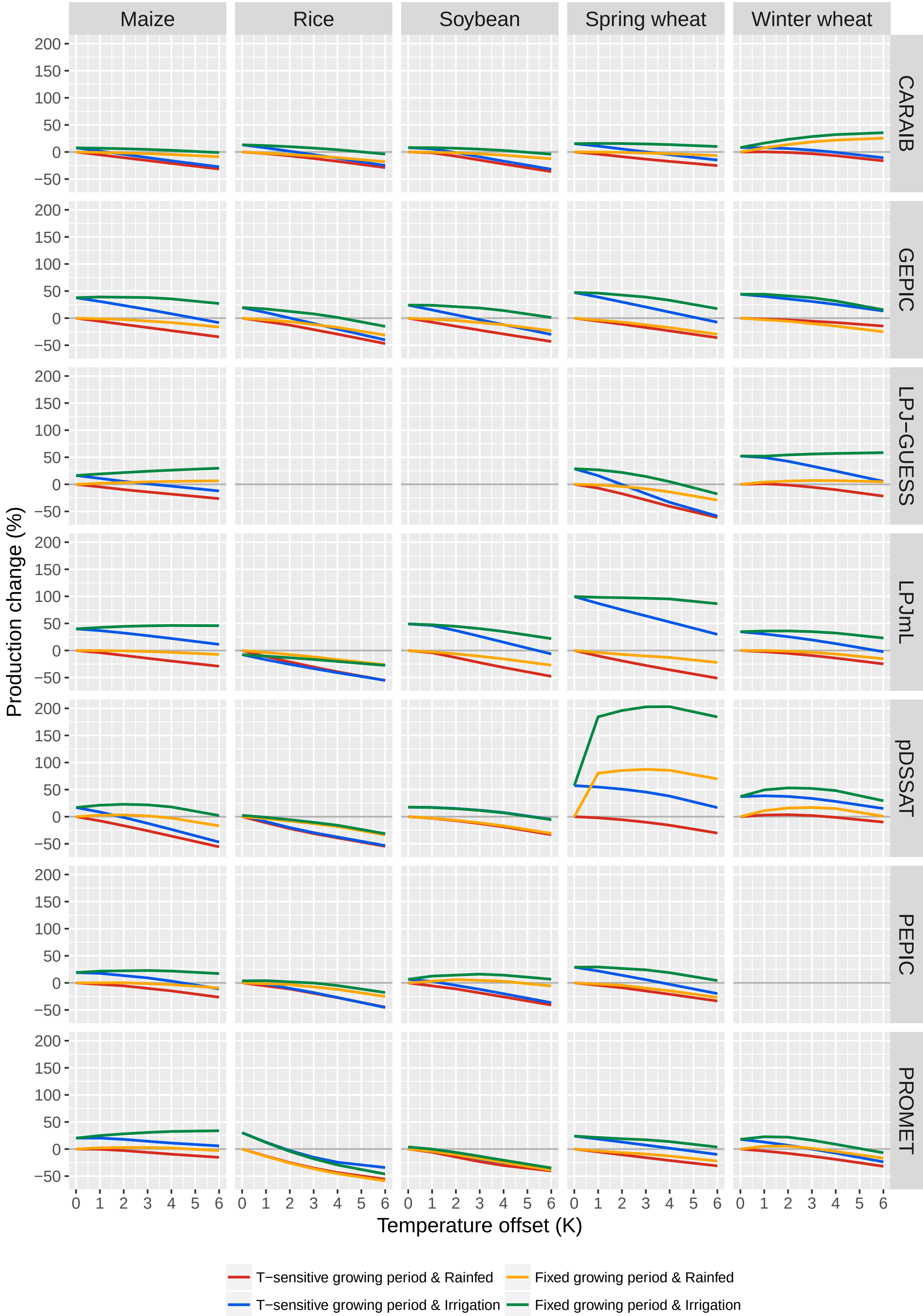

Figure S11. As Figure 3 but for each GGCM.

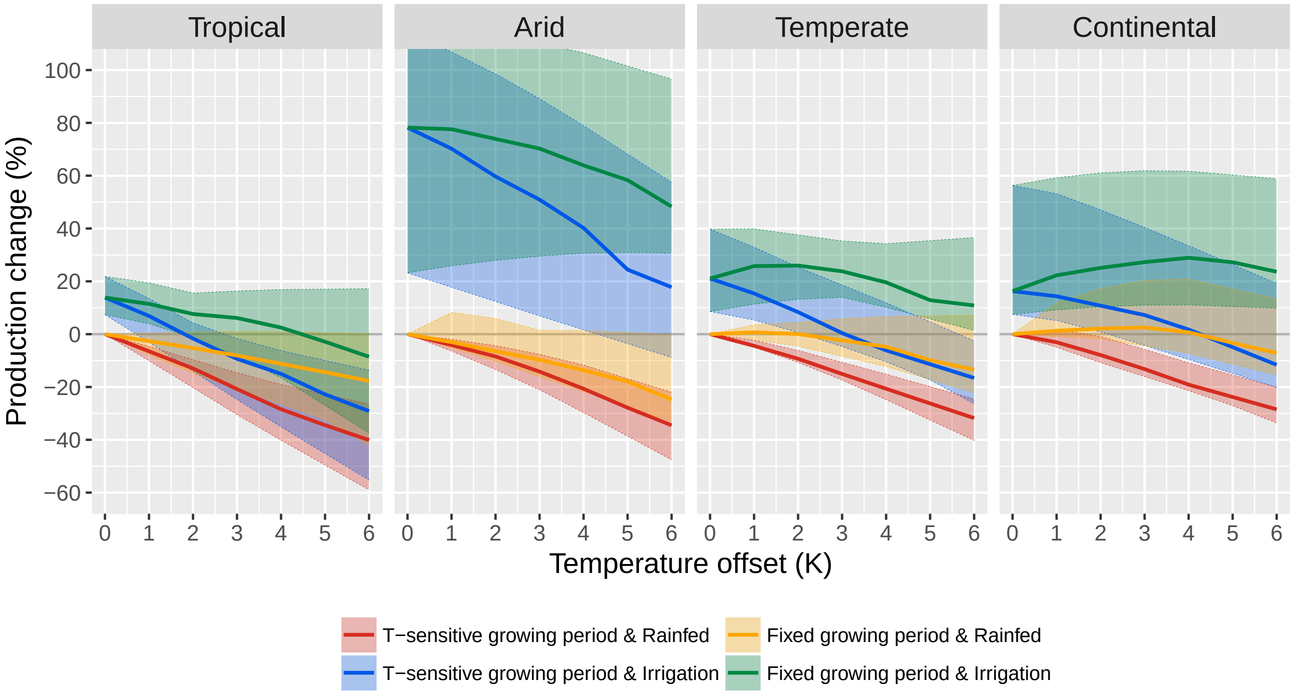

Figure S12. As Figure 3a, but for the Kppen-Geiger climate zones.

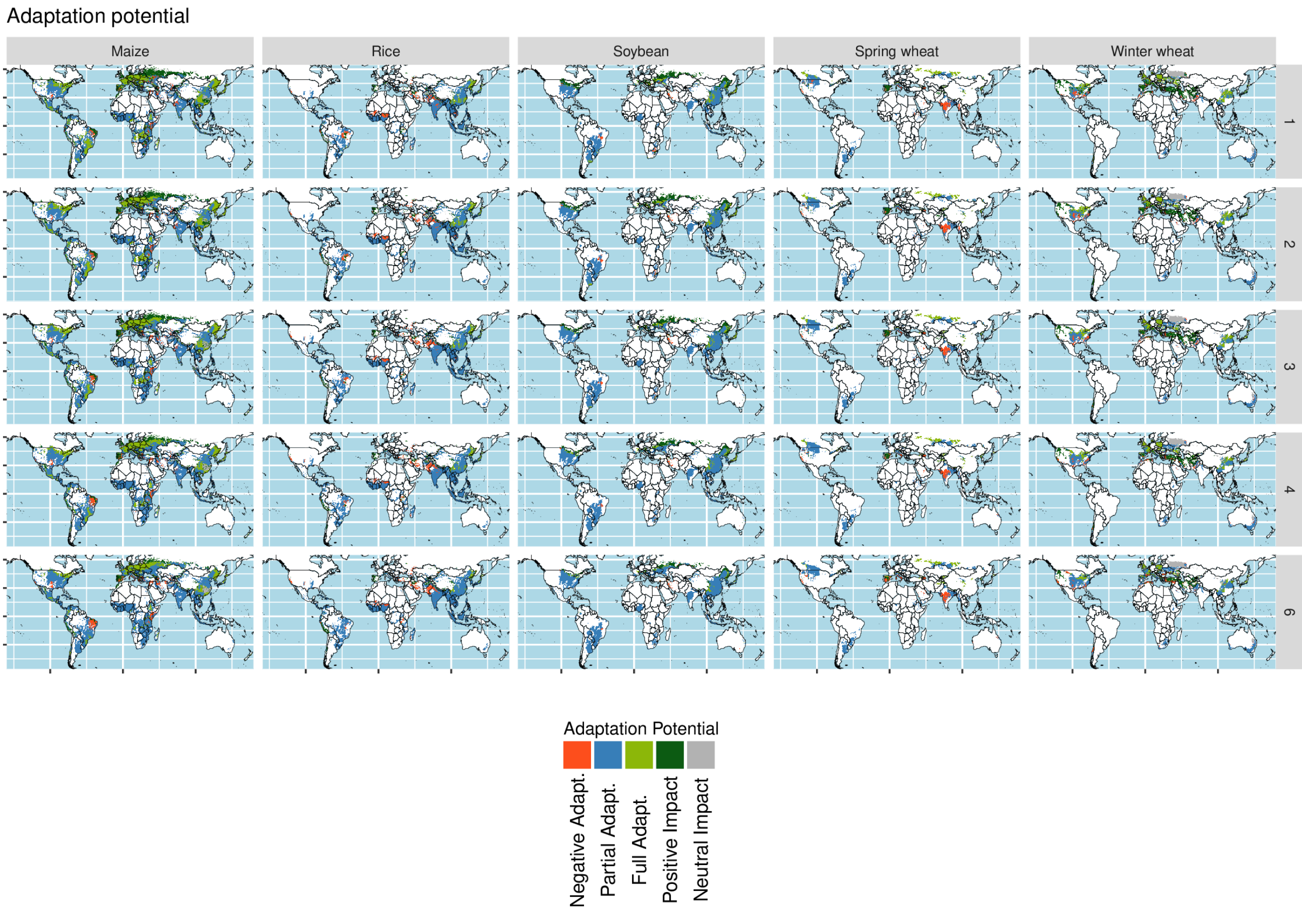

Figure S13. As Figure 4a, but for each temperature offset.

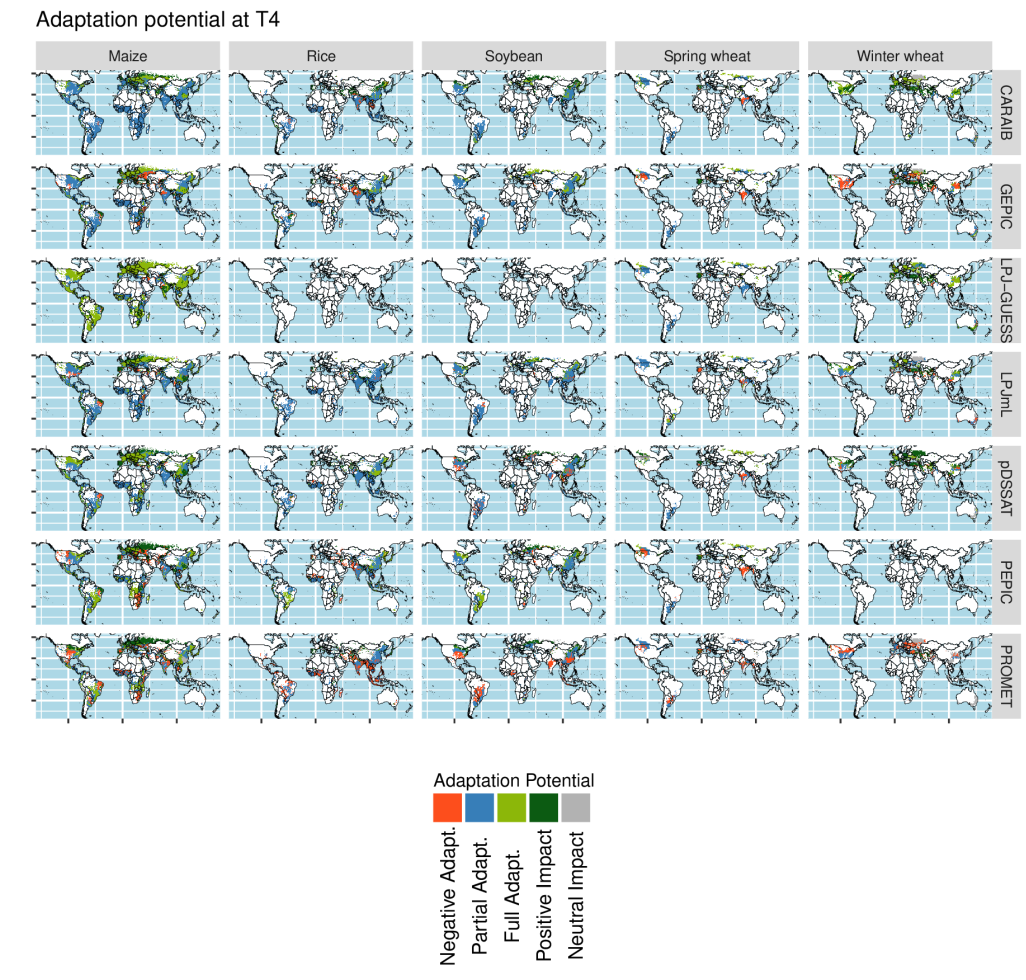

Figure S14. As Figure 4a, but for each GGCM.

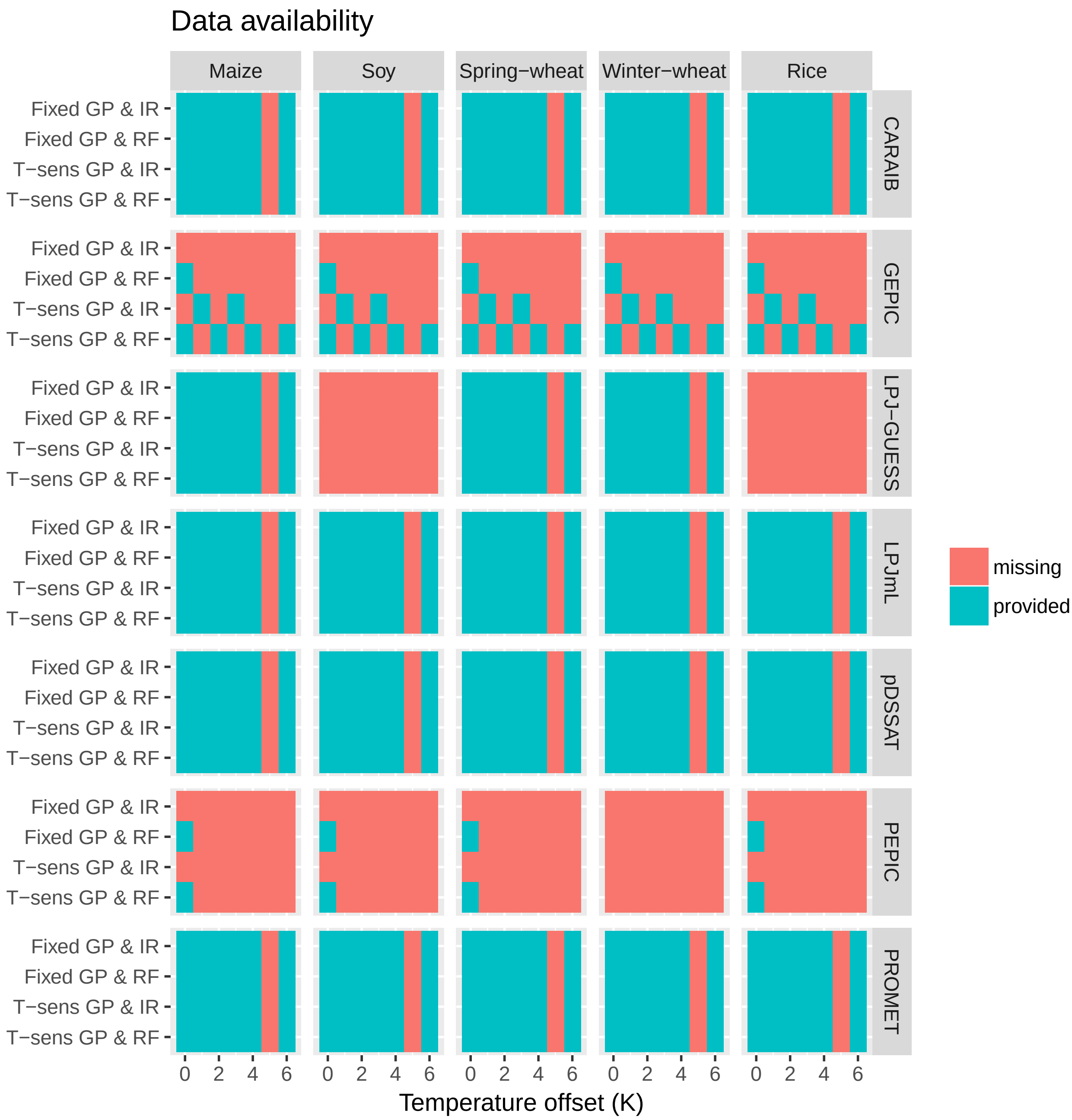

Figure S15. Available crop model simulations at CO_2 mixing ratio of 660 ppm for each model, crop, temperature offset and management setting used in this study. Simulation setups missing (except for LPJ-GUESS rice, LPJ-GUESS soy, GEPIC all crops and PEPIC all crops) are interpolated as described in Section 2.2.

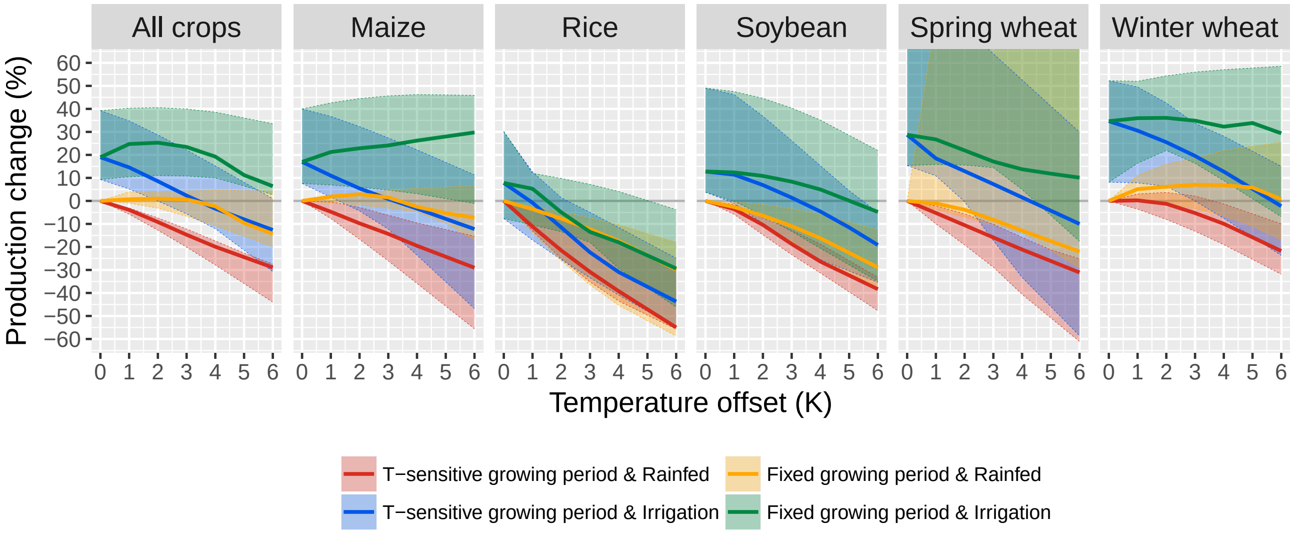

Figure S16. Adaptation at CO_2 mixing ratio of 360 ppm. As Figure 3, but for a subset of GGCMs that provided also the full set of simulations at CO_2 mixing ratio of 660 ppm. To be compared to Figure S17.

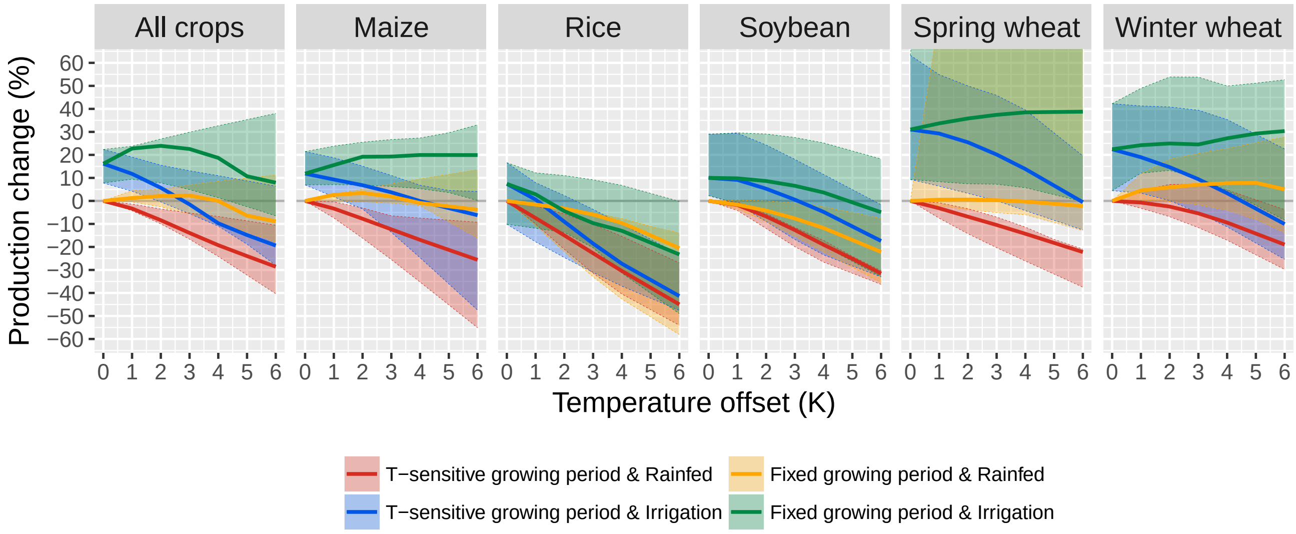

Figure S17. Adaptation at CO_2 mixing ratio of 660 ppm. As Figure 3, but for a subset of GGCMs that provided also the full set of simulations at CO_2 mixing ratio of 660 ppm. To be compared to Figure S16.

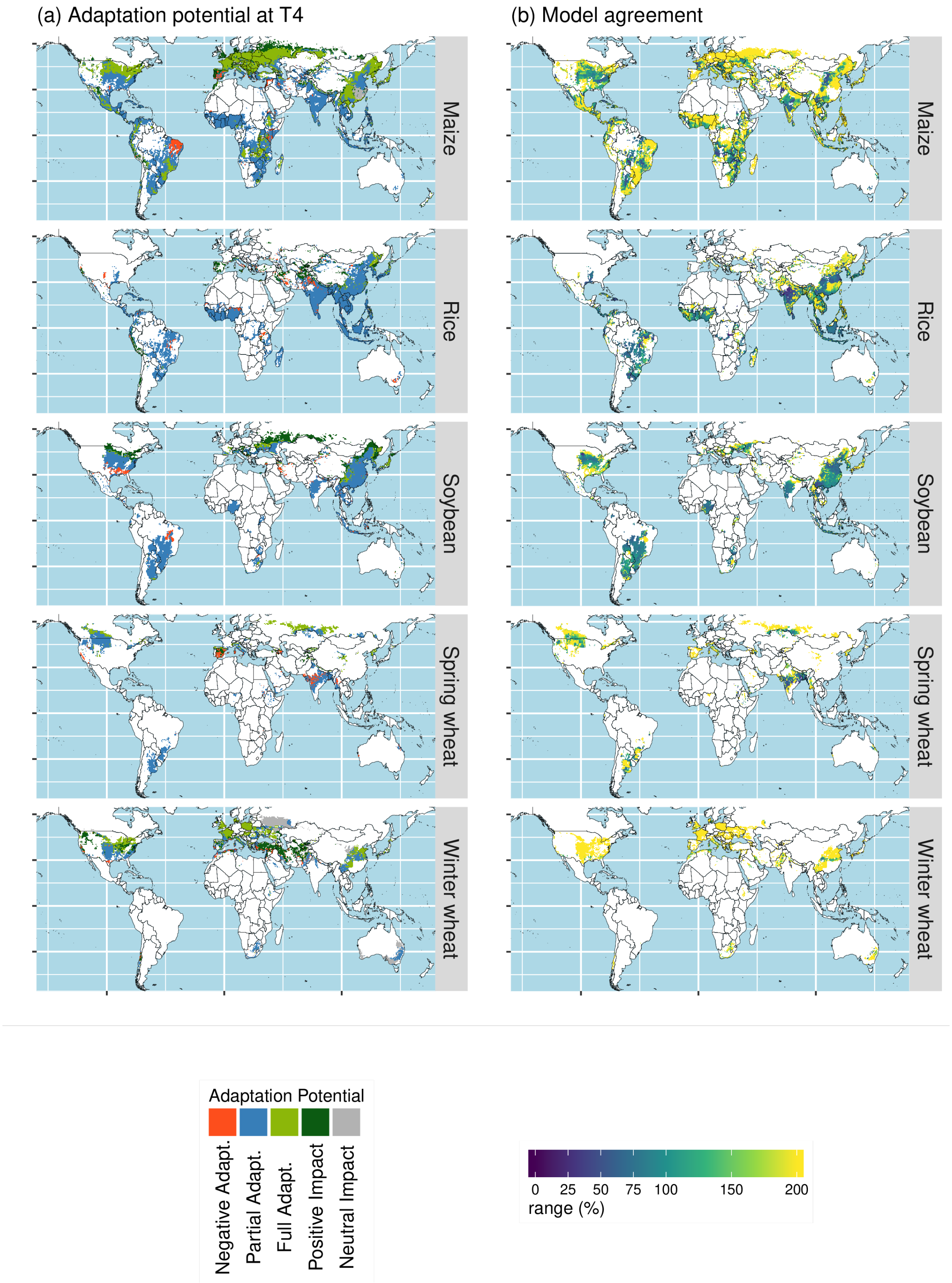

Figure S18. As Figure 4a but at CO_2 mixing ratio of 660 ppm.