Supplemental Material

The GGCMI Phase 2 experiment: global gridded crop model simulations under uniform changes in CO_2, temperature, water, and nitrogen levels (protocol version 1.0)

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S1 Cultivation Areas

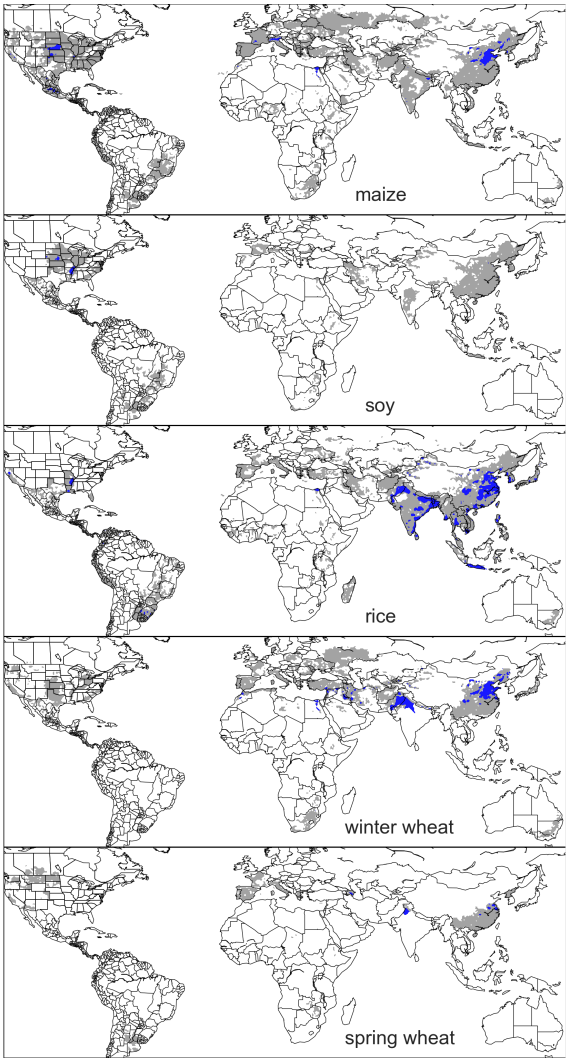

Figure S1: Presently cultivated area for irrigated crops in the real world. The blue contour area indicates grid-cells with more that 20,00 hectares of crop cultivated. The gray contour shows area with more that 10 hectares cultivated. Data from the MIRCA2000 data set for maize, rice, and soy. Winter and spring wheat areas are adapted from MIRCA2000 data and sorted by growing season.

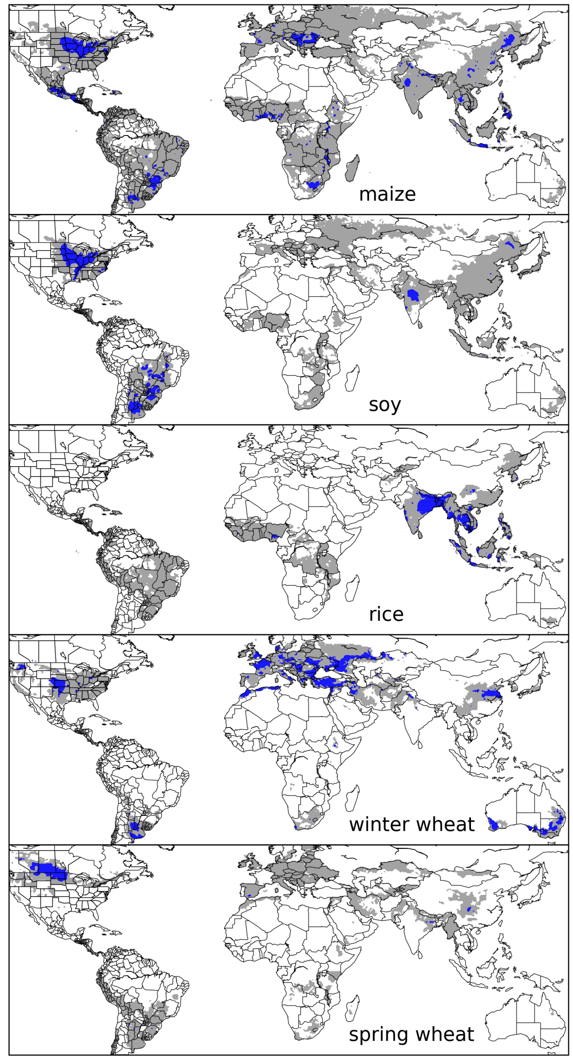

Figure S2: Presently cultivated area for rain fed crops in the real world. Conventions as in Figure S1. This figure repeats manuscript Figure 1 for ease of comparison.

S2 Reanalysis Climate Products

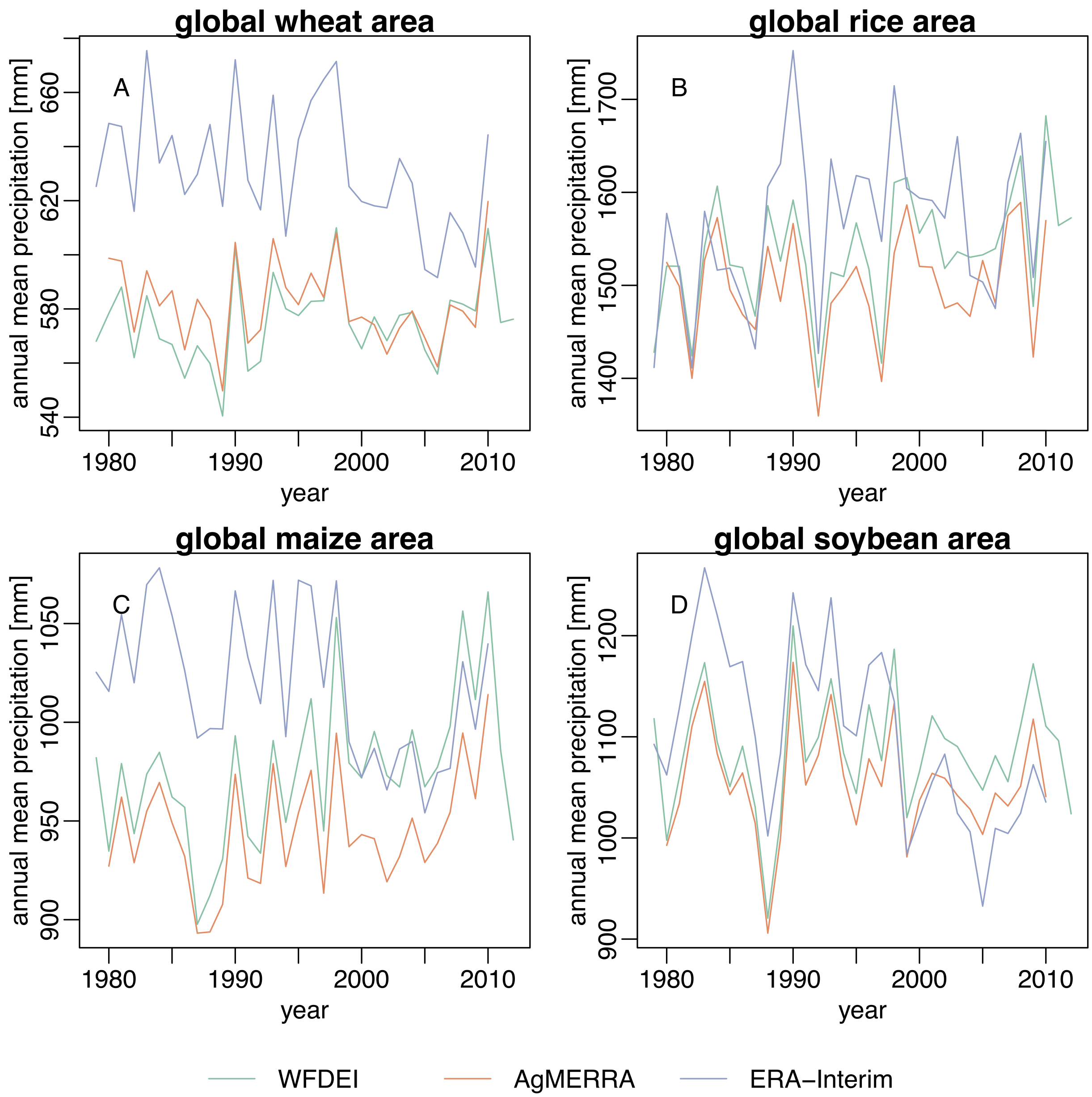

Figure S3: Comparison across the three reanalysis products used in GGCMI Phase 2. Values are aggregated across cultivation area based on the MIRCA2000 dataset.

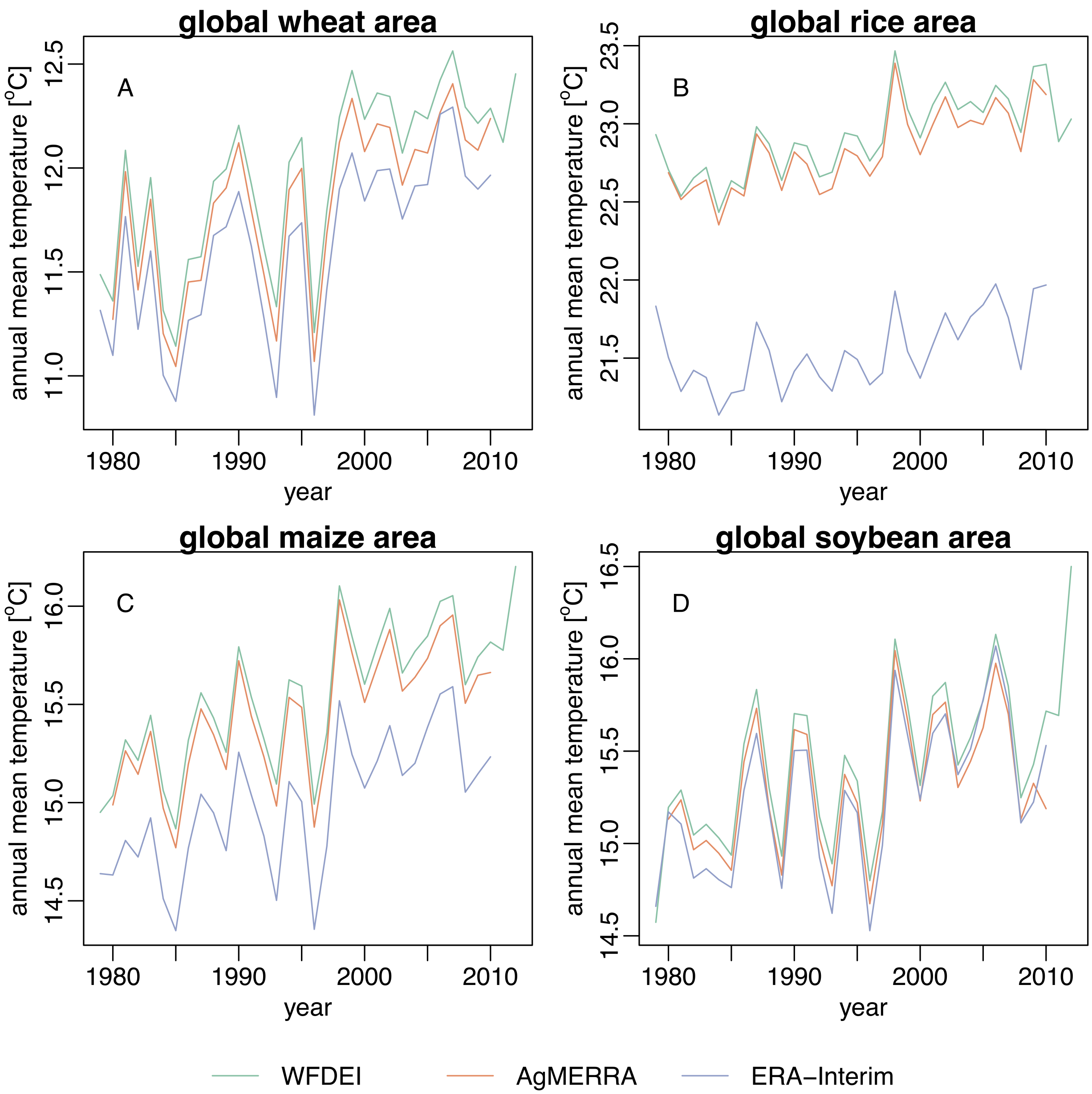

Figure S4: Same as Figure S3 but for temperature.

S3 Model Details

Table S1: Key model details. Notes: (NA where not applicable)
a: D: daily time-step; M: monthly time-step; H: hourly time-step; WG: use monthly climate data interpolated to daily using a weather-generator
b: Ta: average temperature, Tmn: minimum temperature, Tmx: maximum temperature, cld: percentage of cloud cover, sun: fraction of sunshine hours; RH: relative humidity; WS: wind speed; Vap: vapour pressure, Rad: radiation
c: Source of soil property inputs (e.g., source of basic soil properties), plus method for manipulation to derive parameters required by the model); AWC: Available Water Capacity 141; HYD: hydraulic soil parameters; THM: thermal parameters; HWSD: Harmonized world soil database 142; STC: soil texture classification based on the USDA soil texture classification (http://ufdc.ufl.edu/IR00003107/00001); ISRIC-WISE 143; ROSETTA 144
d: Number of years for spin up (x); OM: organic matter, C: organic carbon; N: organic nitrogen; NH3: ammonia; NO3: nitrate; H2O: soil water; P: phosphorus; CR: crop residues; Tsoil: soil temperature
e: calibration of model parameters other than the ones described in the original model description
f: PHU+V: prescribed externally computed phenological heat unit requirements and vernalization (winter wheat) per crop and grid cell to meet prescribed harvest date on average (1980-2010); HI: harvest index
g: Irrigation rules: depth of soil moisture measured (cm) / lower soil moisture threshold to trigger irrigation (%); / upper soil moisture threshold to stop irrigation (%); / irrigation application efficiency (%); no WS: no water stress
h: Irrigation rules: EPIC-based models: water stress in crop to trigger automatic irrigation (%); / irrigation efficiency - runoff from irrigation water (%); / maximum of annual irrigation volume (mm); / maximum of single irrigation volume allowed (mm); / minimum of single irrigation volume allowed (mm)
i: Remove residue or not (Yes/No)
j: ET0: LSM: land surface model, complex computation of energy and water vapor fluxes

Model	Temporal scale (a)	Climate input variables (b)	Soil input data (c)	Spin-up (d)	specific calibration other than growing season (e)	Crop cultivars (f)	Irrigation rules (g,h)	Crop residue removal (i)	model category	primary production	ET0 (j)
APSIM-UGOE	D	Tmn, Tmx, P, Rad	ISRIC-WISE	Soil OM, C, NH3, NO3, H2O (1)	co2 effects included for maize and soybean	N/A	120/100/no/no water stress	Yes	field scale	Radiation use efficiency	Priestley-Taylor
CARAIB	D, but 2-hourly for photosynth	Tmn, Tmx, P, Rad, RH,WS	HWSD	Soil OM, C, H2O, Tsoil (10)	acclimation of photosynthesis to CO2 and	PHU, HI	80-125*/100/100/100g (*) species-depend	Yes	global ecosystem	photosynthesis	Penman
EPIC-IIASA	D	Tmn, Tmx, P, Rad, RH, WS	ISRIC-WISE; ROSETTA; AWC; HYD 137	Soil OM, C, NH3, NO3, H2O, P, CR (20)	none	PHU+V	90/100/2000/500/0h	No	field scale	LUE	Hargreaves
EPIC-TAMU	D	Tmn, Tmx, P, Rad, RH, WS	ISRIC-WISE	Soil OM, C, NH3, NO3, H2O, P, CR (10)	N/A	PHU+V	99/100/9999/100/25h	No	field, region, global	Radiation use efficiency	Penman-Monteith
GEPIC	D	Tmn, Tmx, P, Rad, RH, WS	HWSD	Soil OM, C, NH3, NO3, H2O, P, CR (20)	none	PHU+V, HI (mai)	99/100/2000/1000/0h	Yes, Crop-specific	field scale	LUE	Hargreaves
JULES	3-hourly	T,rain,snow,ShortRad,LongRad, WS,specific humidity, pressure	HWSD	H20, Tsoil (110)	none	PHU	35/-10kPa/-10kPa/100g	Yes	global ecosystem	photosynthesis	LSM
LPJ-GUESS	D	Ta, P, Rad	ISRIC-WISE	C, N-organic, N-inorganic, CR, Tsoil (500 grassland)	none	PHU+V	200/90/100/100g	Yes, 10% left on field from previous cycle	global ecosystem	photosynthesis	Priestley-Taylor
LPJmL	D	Ta, P, cld (or ShortRad, LongRad)	HWSD, STC HYD138, THM 139	C, N, NH3, NO3, H2O, CR, Tsoil (5000 natural vegetation, 390 land use)	none	PHU+V	300/90/100/variesg	Yes, 10% left on field from previous cycle	global ecosystem	photosynthesis	Priestley-Taylor
ORCHIDEE-crop	Half-hourly	Tmn, Tmax, P, Rad, RH, WS	NA	H2O (1)	none	PHU+V	200/90/100/variesg	Yes, does not affect yield	global ecosystem	photosynthesis	Penman-Monteith
pDSSAT	D	Tmn, Tmx, P, ShortRad	Global Soil Dataset for Use in Earth System Models	Soil OM, C, NH3, NO3, H2O (1)	none	PHU+V (for anthesis and maturity)	mai and soy: 40/99/100/100 ric, swh, wwh: 40/80/100/100	Yes, does not affect yield	field scale	Radiation use efficiency	Priestley-Taylor (default), Penman-Monteith (optional)
PEPIC	D	Tmn, Tmx,P, Rad, RH, WS	ISRIC-WISE	Soil OM, C, NH3, NO3, H2O, P, CR (20)	none	PHU+V	90/100/1000/500/1h	Yes	field scale	LUE	Penman-Monteith
PROMET	H	T,P,ShortRad,cld,LongRad,WS, RH,P	Derived from HWSD	H2O(5), Tsoil(5)	none	PHU+V	no WS	No	global ecosystem	photosynthesis	LSM

Calibration procedures for growing season recalibration in the A1 scenarios:

- APSIM-UGOE: default cultivars with forced harvest at given maturity days
- CARAIB: harvest forced on the same day as in the A0 simulation
- EPIC-IIASA: Potential Heat Units (PHU) were calculated for each crop and grid cell based on grid-specific input sowing and harvesting dates using the background weather dataset
- EPIC-TAMU: An algorithm was written to calculate the heat units required to reach maturity for a particular crop and location. These heat units were calculated for each year in the weather record, and PHU was set as the average heat units from this time series.
- GEPIC: Crop- and pixel-specific potential heat units (PHU) were estimated ex ante based on input sowing dates, harvest dates, and 31 year monthly means of minimum and maximum temperatures using a program provided by the EPIC development team. The resulting long-term average PHU were subsequently used as a model input parameter.
- JULES: Thermal times from emergence to flowering and flowering to harvest, were created by iteratively working out which thermal times would produce the right harvest dates for each crop in each gridbox (using the sowing and maturity dates provided by GGCMI and calculating harvest dates using table 11 in the Phase 1 protocol) using a 3hrly WFDEI climatology for the years 1991-2000 inclusive. The thermal time between emergence and flowering was assumed to be a crop-specific constant fraction of the thermal time between emergence and harvest. These thermal times were then prescribed as crop- and grid-cell specific values.
- LPJ-GUESS: In a preparatory simulation run with unlimited growing season length, the accumulated phenological heat units (PHU) at the given maturity date were recorded per crop, year and grid cell. These heat units were averaged over all years and then prescribed as crop- and grid-cell specific values.
- LPJmL: In a preparatory simulation run with unlimited growing season length, the accumulated phenological heat units (PHU) at the given maturity date were recorded per crop, year and grid cell. These heat units were averaged over all years and then prescribed as crop- and grid-cell specific values.
- ORCHIDEE-crop: Crop-specific thermal times from emergence to flowering and flowering to harvest were created from default datasets of cultivars, by a testing simulation during 2000s, we chose the cultivar best matching the calendar provided by the protocol.
- pDSSAT: ran a calibration simulation in the baseline period, proportionally adjusting the phenological GDD parameters (p1 and p5 for grains) to produce thr target average growing season length over the baseline period. The resulting calibrated parameters were used for future simulations.
- PEPIC: used averaged month temperature across the study period, prescribed growing season, and crop-specific base temperature to estimate PHU for each grid and crop
- PROMET: In a preparatory sensitivity analysis, simulation runs with unlimited growing season length were carried out for different cultivars. A 'cultivar factor' was set to a crop, year and grid cell specific value that reproduces the statistical growing season. This 'cultivar factor' was averaged over all 30 years and then prescribed as crop- and grid-cell specific values.

S4 Results

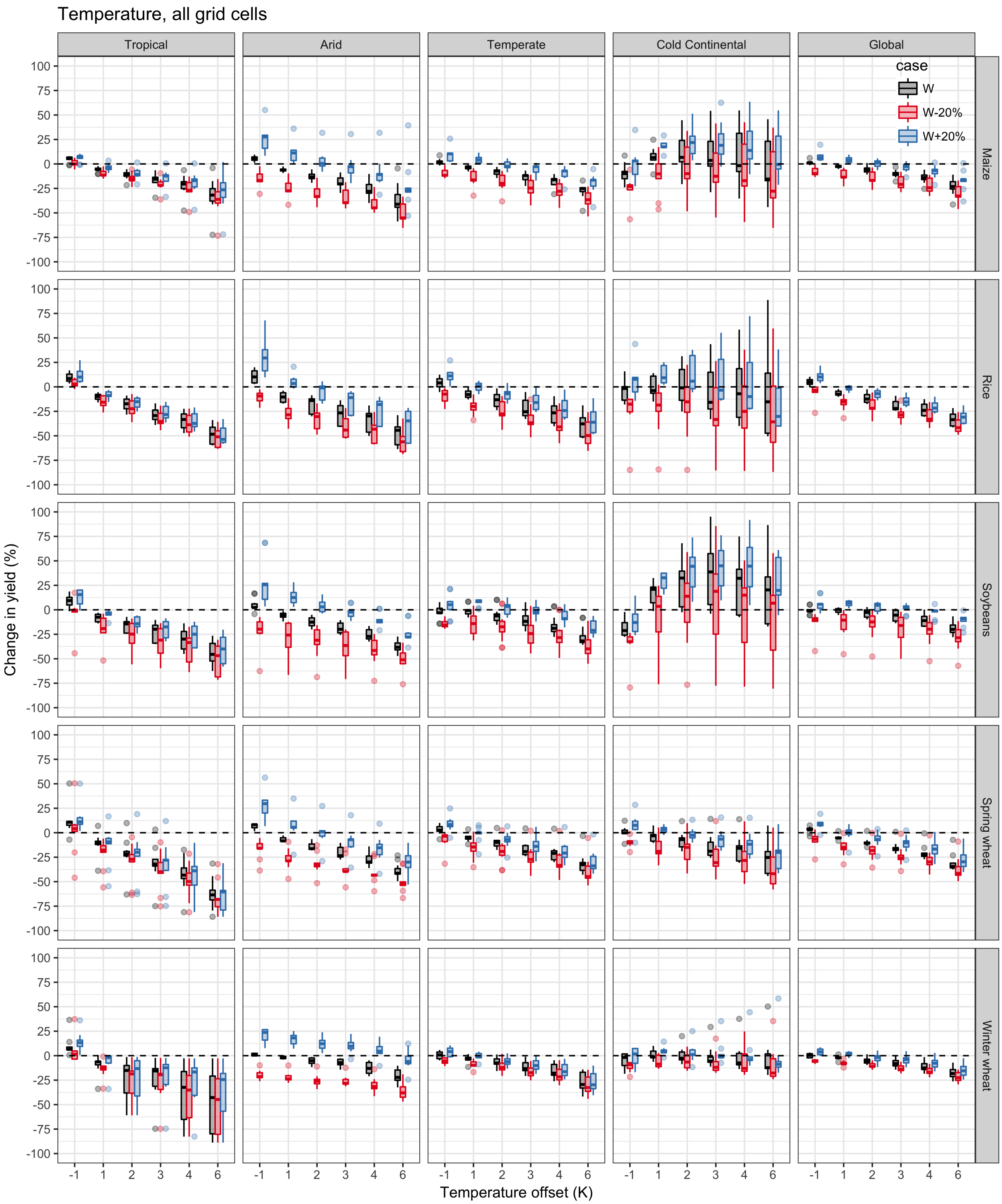

Figure S5: Same as main Figure 5a for all crops.

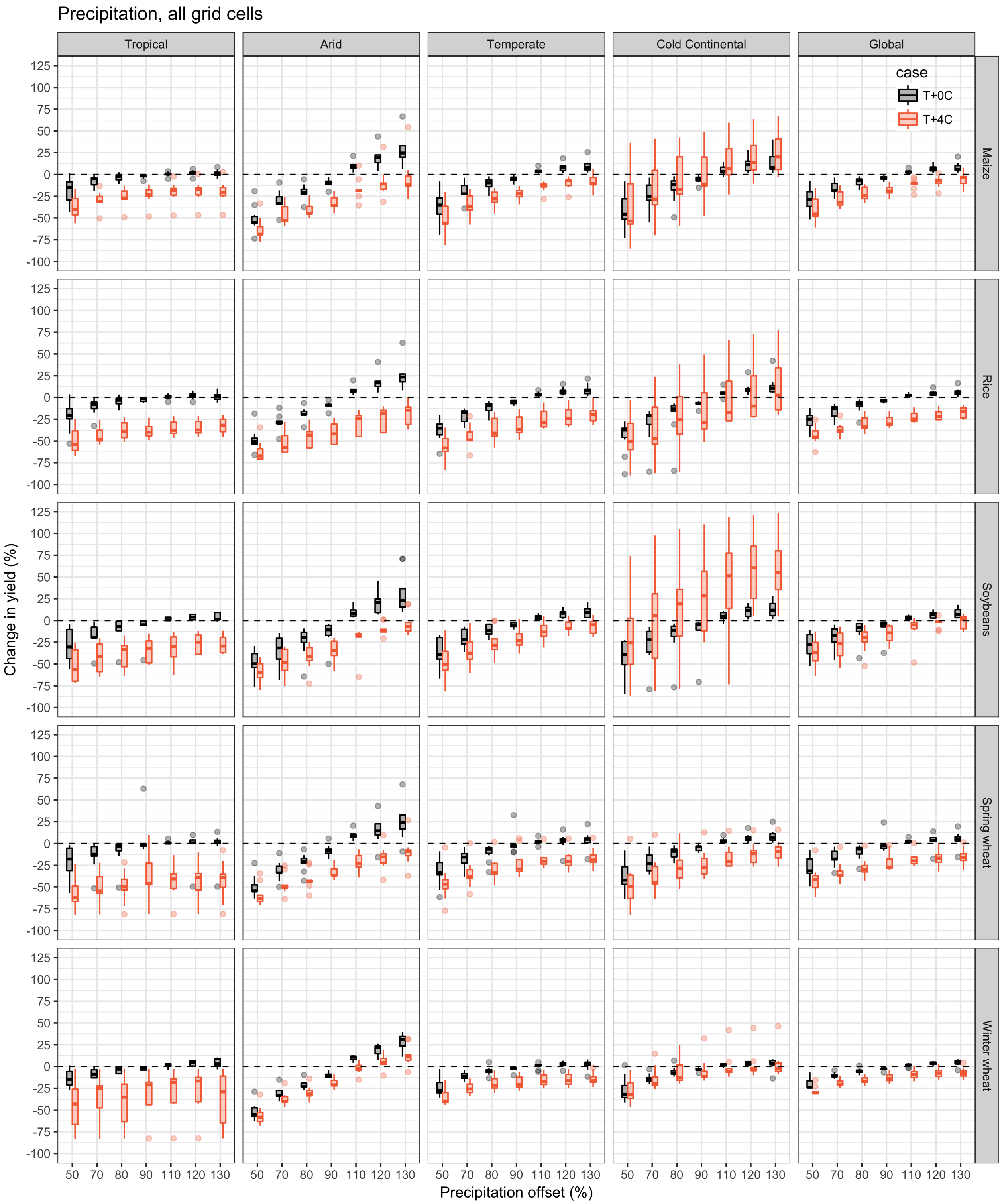

Figure S6: Same as main Figure 5b for all crops.

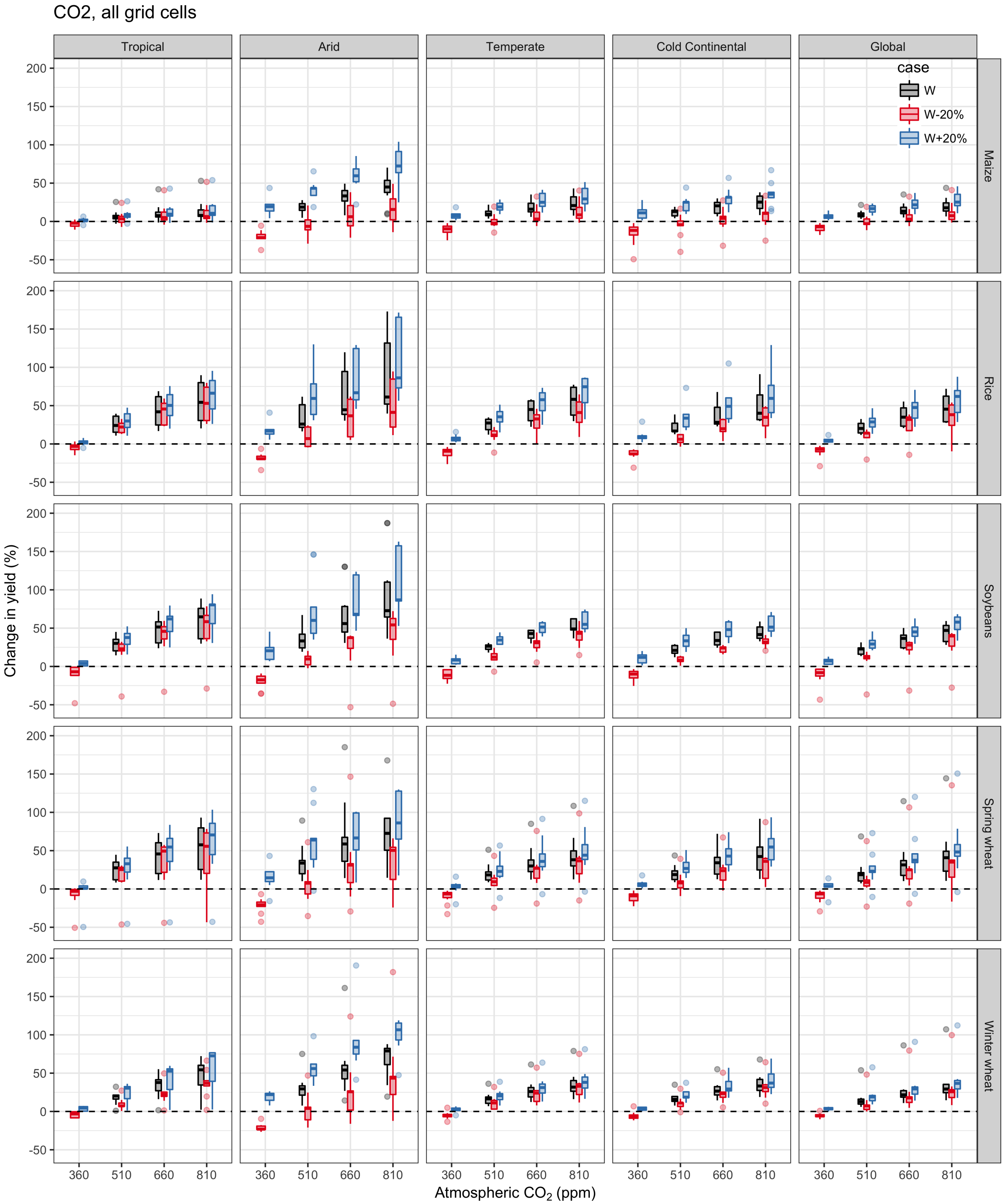

Figure S7: Same as main Figure 6a for all crops.

Figure S8: Same as main Figure 6b for all crops.

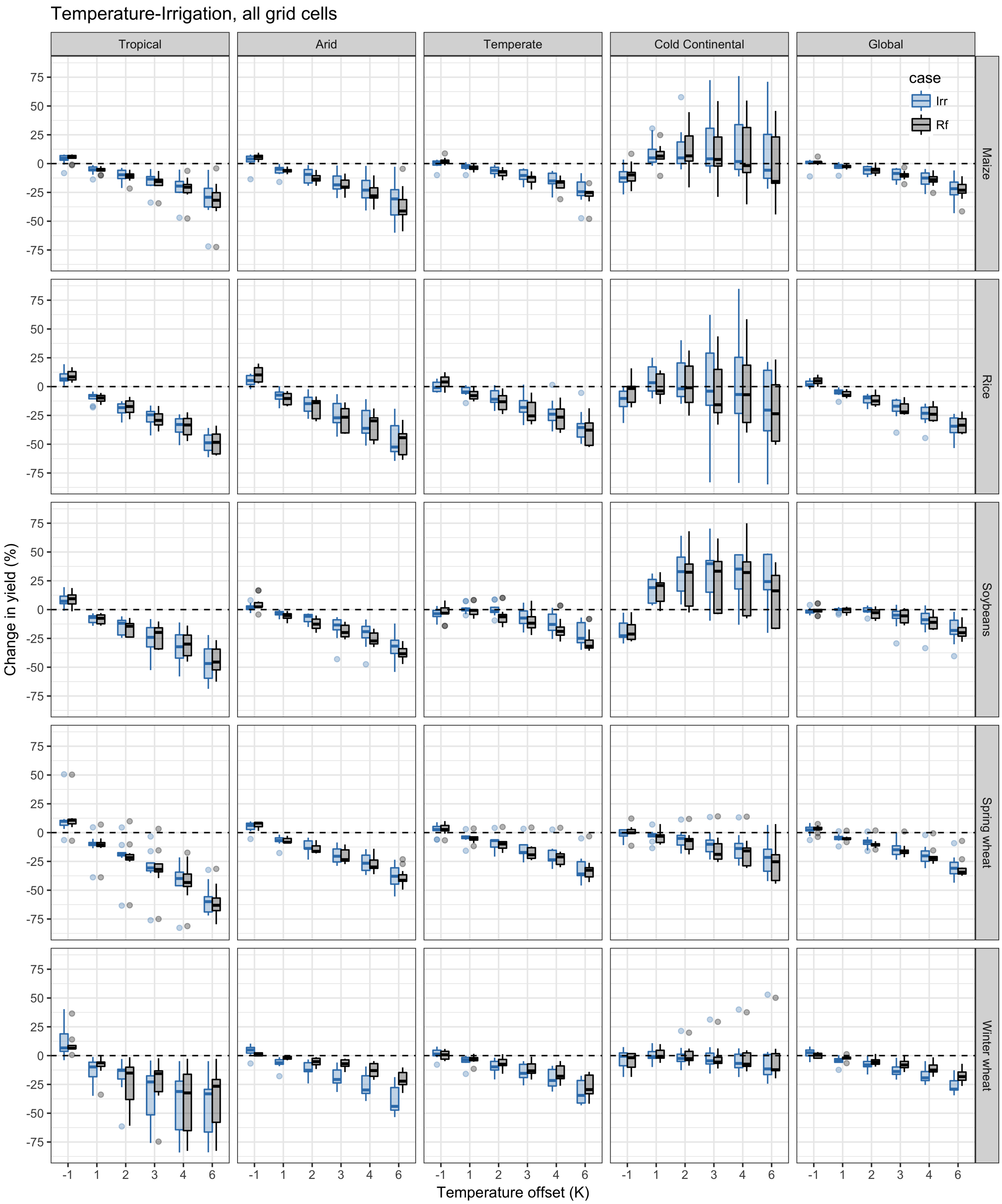

Figure S9: Same as main Figure 5a for all crops. Irrigated crops compared to rainfed. Note that yield change for irrigated crops is from the irrigated baseline, which is typically higher than rainfed.

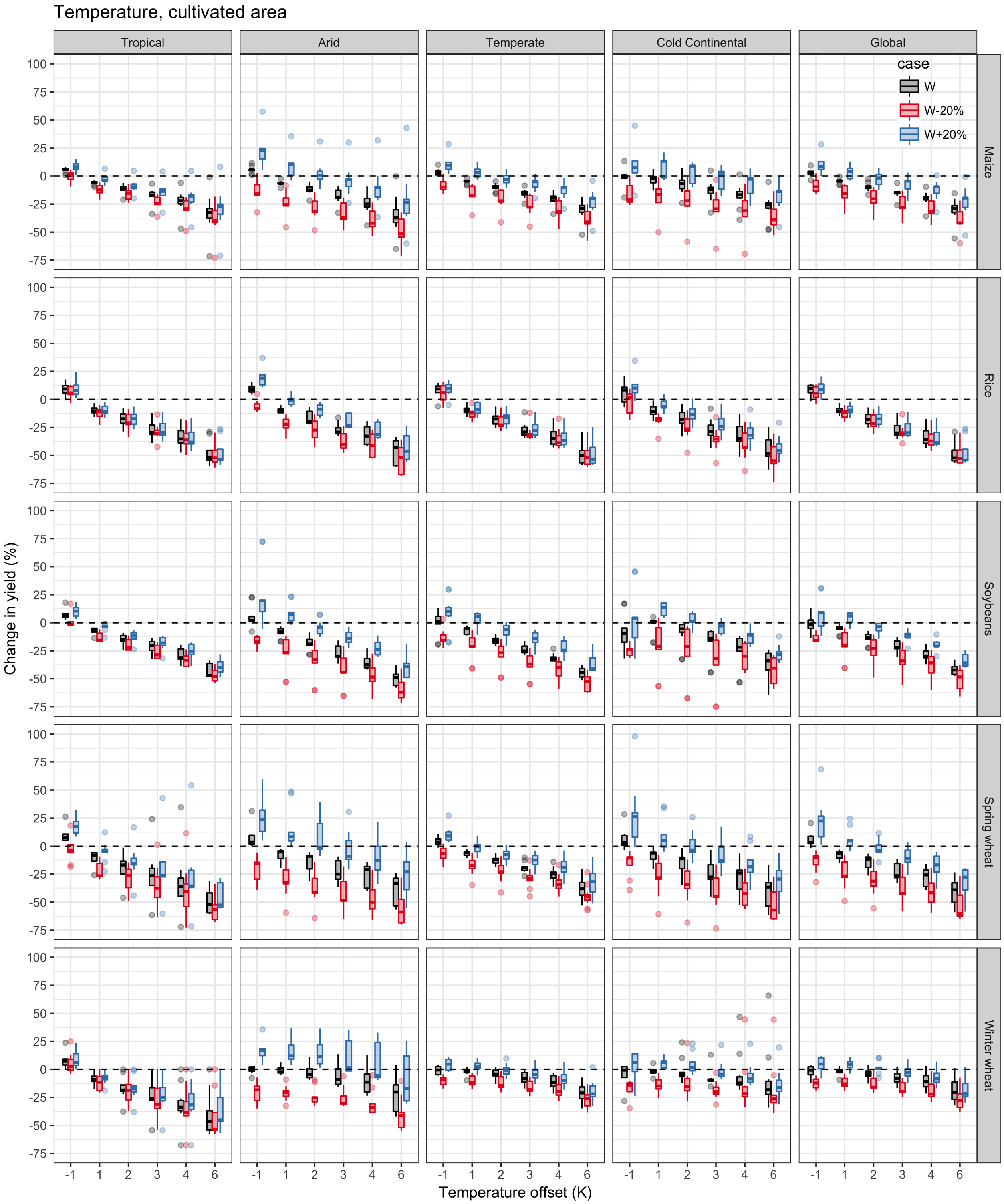

Figure S10: Same as main Figure 5a for all crops. Only over cultivated area.

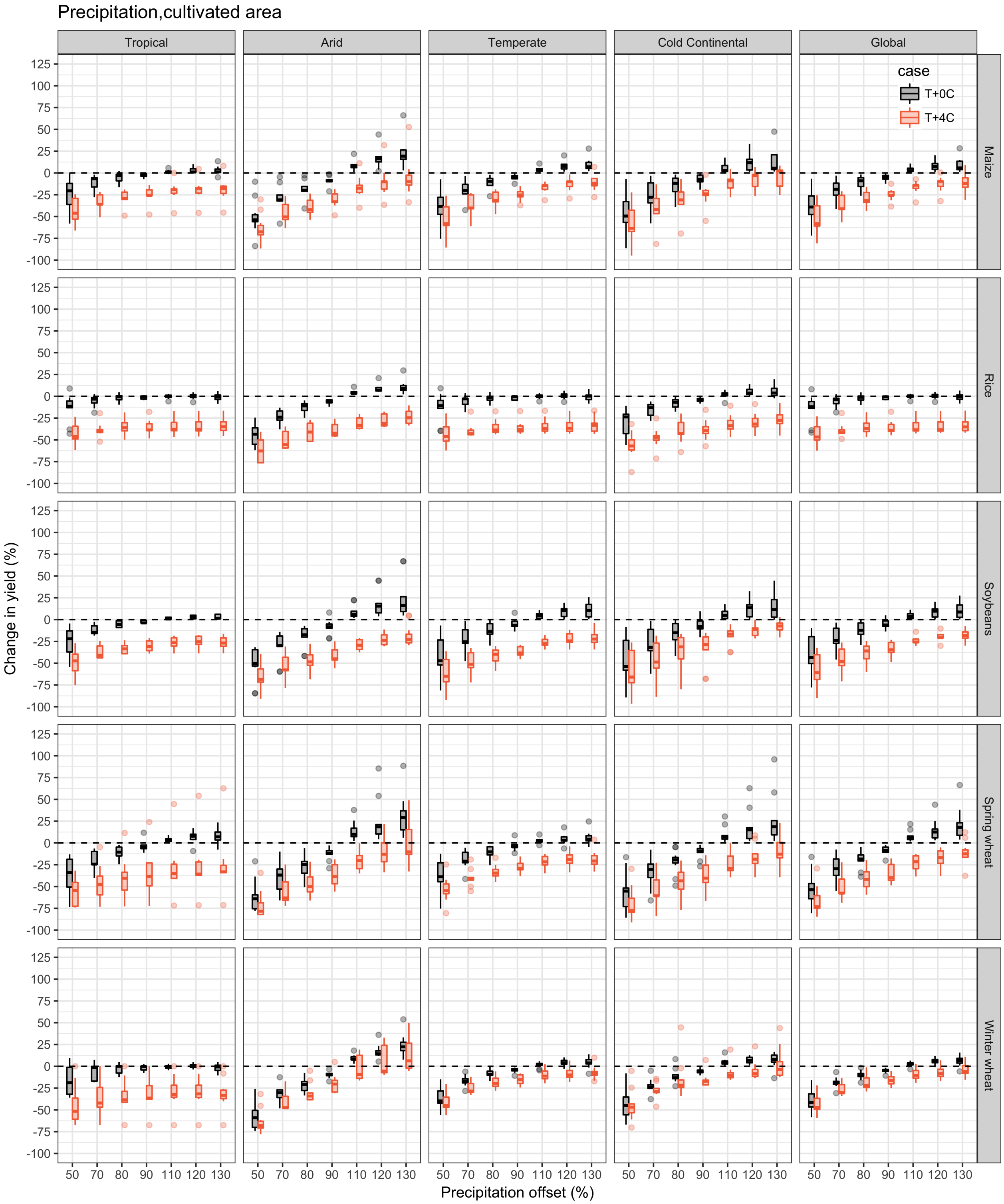

Figure S11: Same as main Figure 5b for all crops. Only over cultivated area.

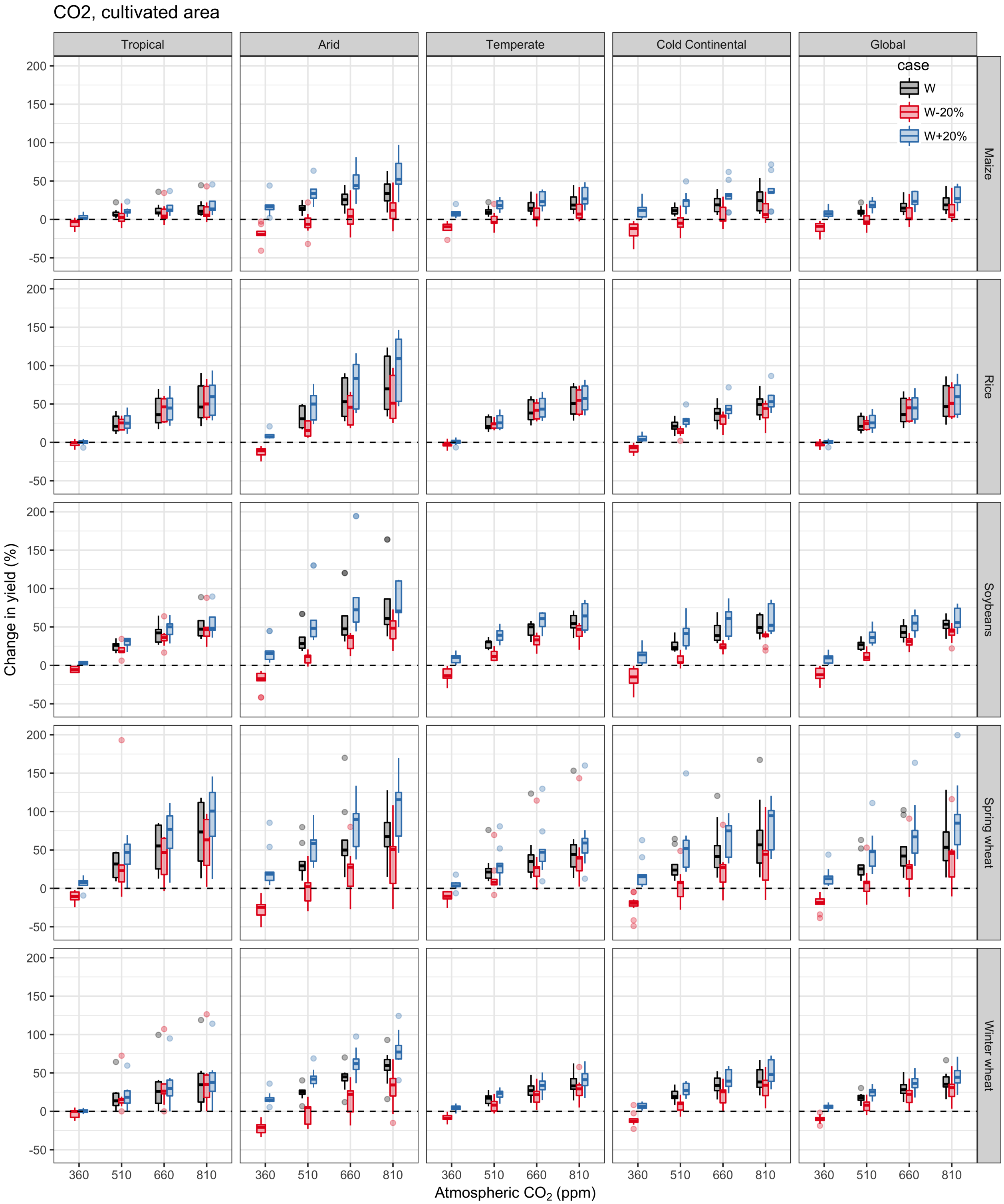

Figure S12: Same as main Figure 6a for all crops. Only over cultivated area.

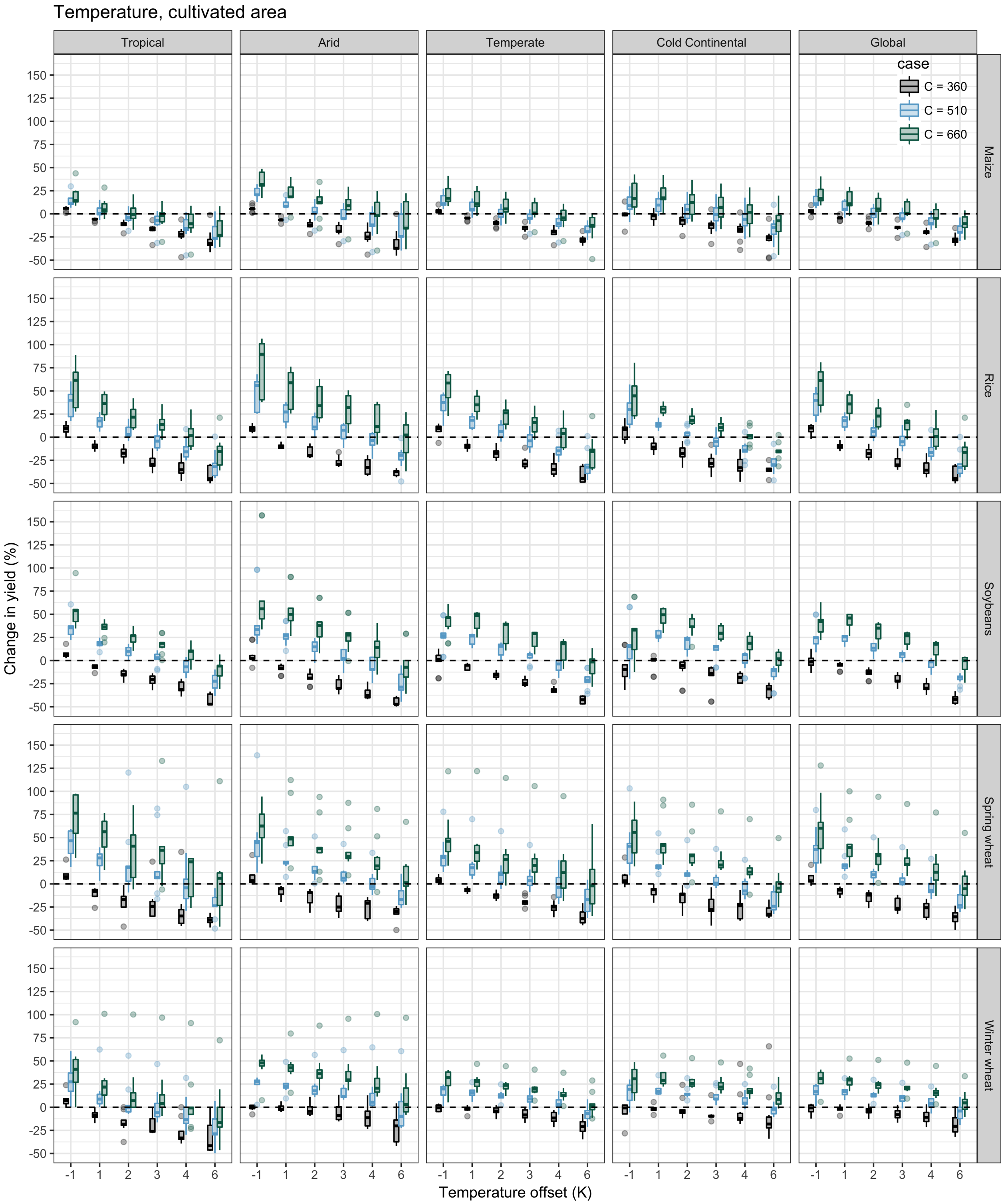

Figure S13: Same as main Figure 6b for all crops. Only over cultivated area.

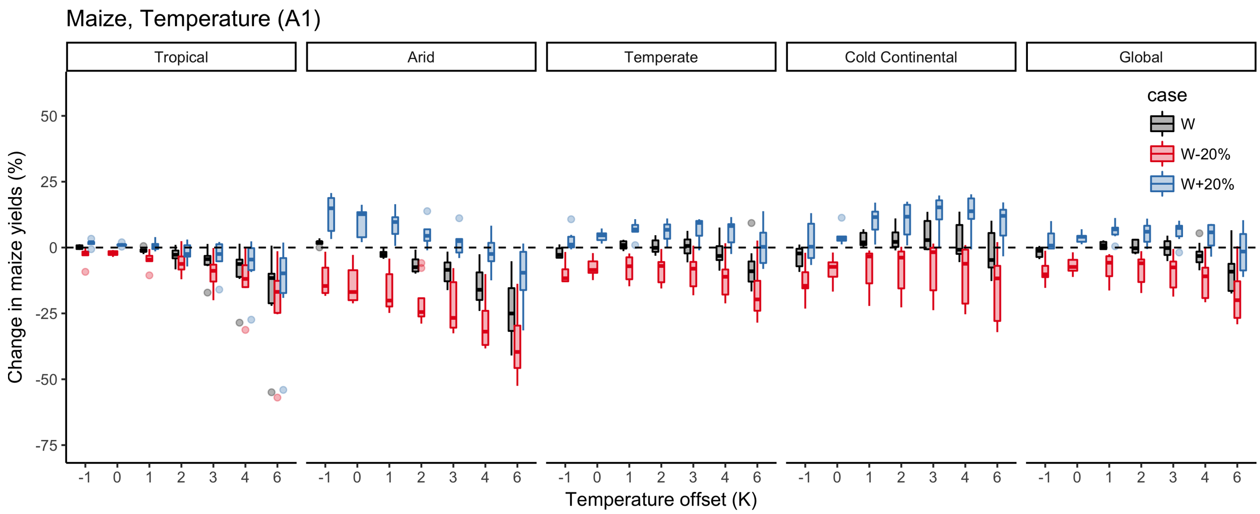

Figure S14: Same as main Figure 5a for except for A1 simulations where the growing season in held constant under warming.

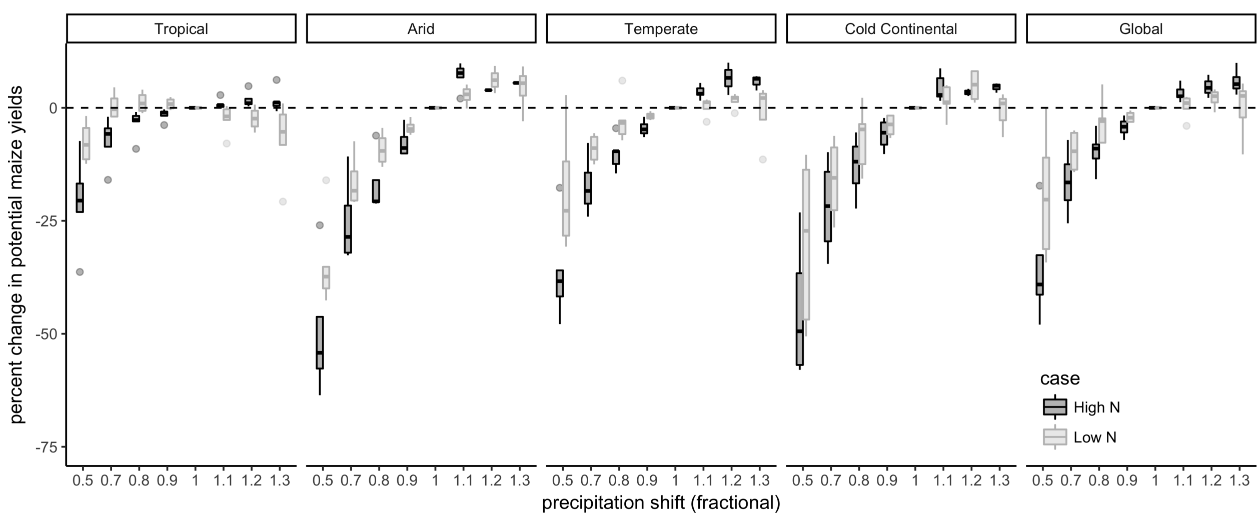

Figure S15: Same convention as main Figure 5b except for maize across the precipitation and nitrogen dimensions.

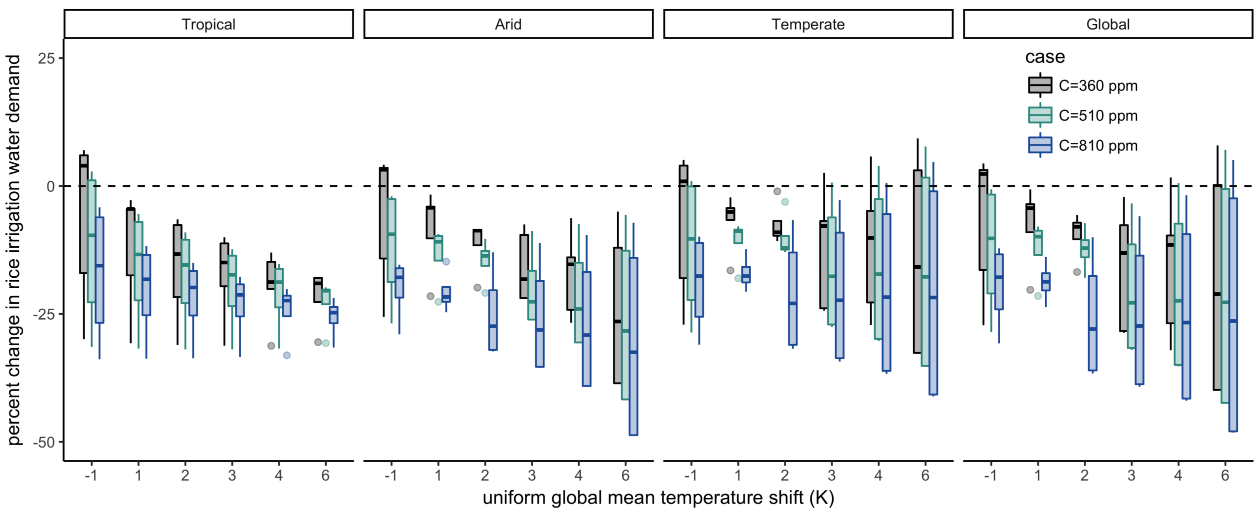

Figure S16: Same convention as main Figure 6b except for irrigation water demand instead of yield.