Supplementary Information

Soil Organic Carbon and Nitrogen Feedbacks on Crop Yields under Climate Change

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The supplementary information contain 21 pages, 8 tables and 11 figures.

<u>Simulations protocol</u>

This paper presents the results of the AgMIP Soils and Crop Rotation Initiative. The initiative is focused on crop and soil models able to simulate the effects of management strategies on yield, along with soil carbon and nutrient fluxes. We chose five maize models and seven wheat models that had been part of AgMIP wheat (9, 10) and maize (11) pilot studies (Table S1).

Simulations were carried out at four locations for each crop. Wheat simulations were completed for sites located in the Netherlands (Wageningen), Argentina (Balcarce), India (New Delhi), and Australia (Wongan Hills). Maize sites were located in France (Lusignan), USA (Iowa, Ames), Brazil (Rio Verde), and Tanzania (Morogoro). Crop management treatments are representative of common practice in each region (*9,11*).

Simulations were carried out with long-term, measured daily climate data for each site over the 1980-2010 period. Climate data included solar radiation, maximum and minimum temperatures, precipitation, surface wind speed, dew-point temperature, relative humidity, and vapor pressure.

Modelers were asked to use the fully calibrated crop model from each pilot study (9, 11). Calibration data included initial soil water and N content (measured), crop management, anthesis and maturity dates (measured), within-season and final leaf area index, biomass, water uptake, N export, grain yield and yield components.

Model simulations were run with similar factorials (temperature, CO_2) as had been done in the respective AgMIP pilots (*9, 11* - Table S2). Finally, the models were run in annually reinitialized soil conditions and in continuous simulation modes. Site characteristics and crop management operations are given in Table S3.

Dynamics of Soil Organic Carbon

Each modeling group was provided with initial SOC content. SOC pools were initialized by each modeling group separately to better represent the structure of each model. The relative changes in SOC between the first and last years of simulation were expressed as a relative % change and were computed following equation 1:

$$\Delta SOC_i[\%] = 100 - \frac{SOC_i - SOC_{1980}}{SOC_{1980}} \quad (1)$$

where *i* is a given year between 1981 and 2010. Results were then expressed as percentage of change relative to the initial SOC content.

Crop model uncertainty under temperature changes

Crop models may have different responses to increased temperature, thus these responses were computed individually for each crop model according to Eq. 2:

$$\frac{\Delta y_{i,m,t}}{\Delta t} = \frac{y_{i,m,t} - y_{i,m,t=0}}{t - t0}, \forall\ i, m\ and\ t > 0°C \quad (2)$$

where *y* is a crop model output variable, *i* and *m* are a given year and site, and *t* is a temperature treatment. For each site, individual model responses were then aggregated over all models, years and temperature treatments.

Crop model ensemble

According to previous studies (*12, 13*), the number of models we used (five maize models and seven wheat models) is considered sufficient to reduce uncertainty to an acceptable level. As suggested by (12), the median outputs (yields, SOC, etc.) were used as the best estimator of the model ensembles

Multiple linear regression

The productivity (yields and residues) data of the wheat- and maize-fallow cropping systems were put in relation with SOC dynamics and temperature scenarios.

To analyze the contribution of the different factors, a multiple linear regression, following equation 3, was fitted to the simulated data. This allowed identification of the contribution of each factor and their interaction:

$$Productivity = c_0 + c_1 \times T + c_2 \times SOC + c_3 \times T \times SOC \quad (3)$$

where *Productivity* is either the simulated yield or the amount of crop residues, *T* is the temperature treatment, *SOC*, is the soil organic carbon content (measured in percent content, *i.e.* in kilogram of organic Carbon per kilogram of soil), and c_0 to c_3 are the coefficients of regression.

Supplementary results of continuous model runs (with inclusion of SOC dynamics)

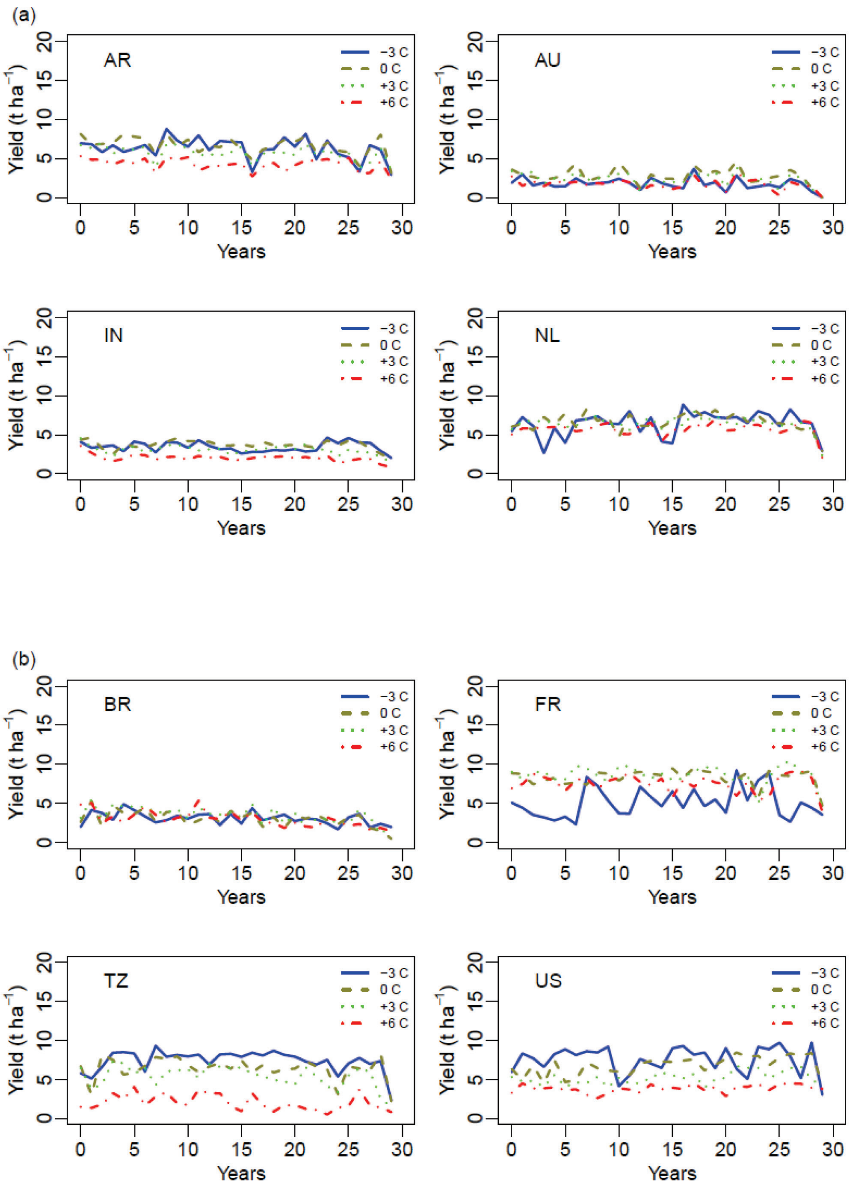

Figure S1.

Yield simulations for the different sites and temperature scenarios and constant CO2 concentration (360 ppm). The lines represent the median of the model ensemble predictions for the site and scenario. The site abbreviations for wheat are: Argentina (AR), Australia (AU), India

(IN); Netherlands (NL); for maize are: Brazil (BR), France (FR), Tanzania (TZ), United States (US).

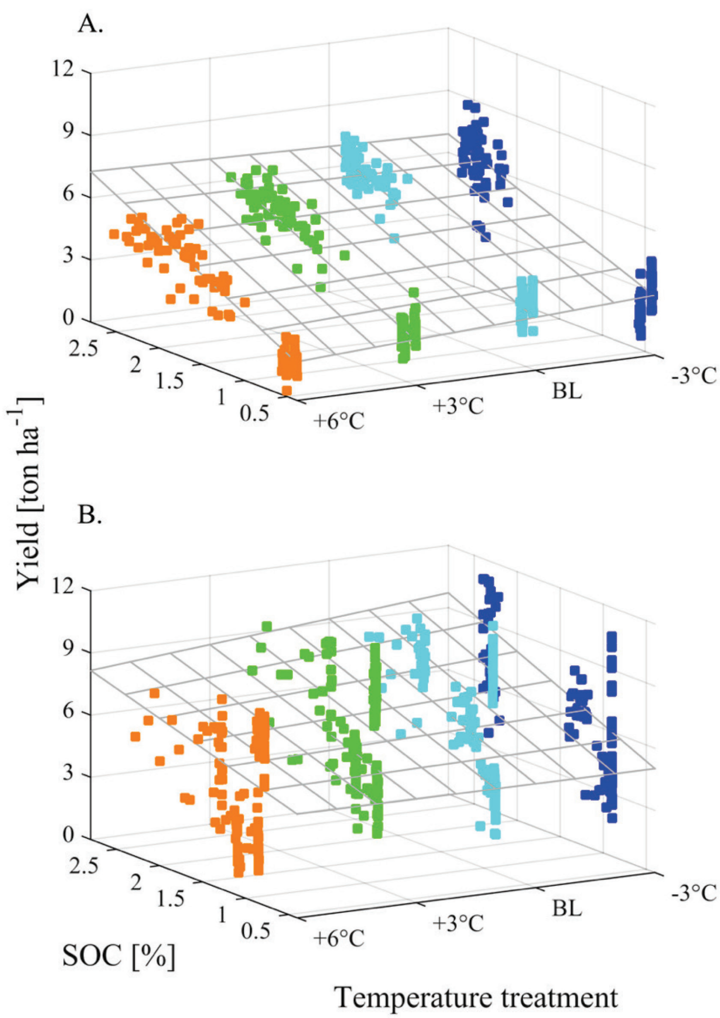

Figure S2.

Three-dimensional plot of simulated yield for wheat (A) and maize (B) sites *vs* SOC and the temperature scenarios. Regression surface fitted to data is represented by the grey lines (according to Eq.3 of supplementary material, Table S6). Each dot represents a site-year simulation of the model ensemble. Different colors represent the temperature treatments. [CO_2] was kept at the baseline (360ppm).

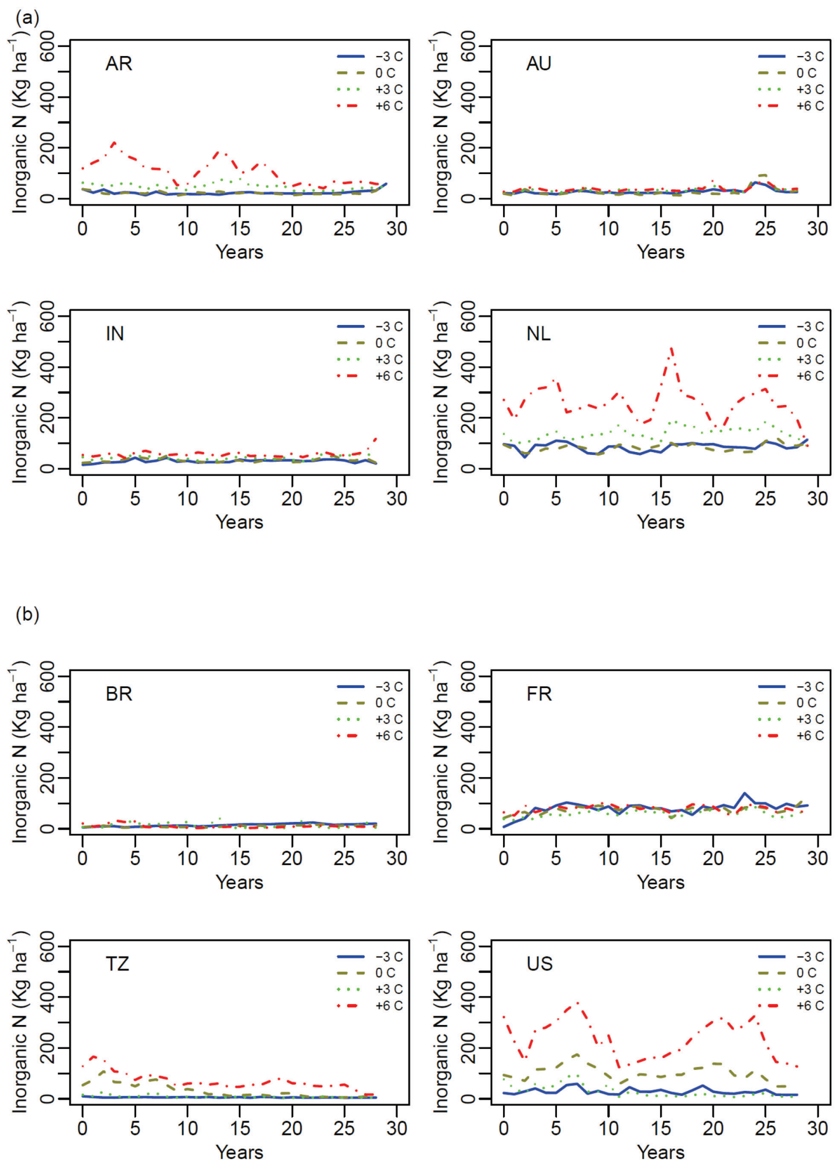

Figure S3.

Simulations of the Soil N-NO_3 until rooting depth at harvest for the different sites, temperature scenarios and constant CO2 concentration (360 ppm). The lines represent the median of the model ensemble predictions for the site and scenario. The site abbreviations for wheat are: Argentina (AR), Australia (AU), India (IN); Netherlands (NL); for maize are: Brazil (BR), France (FR), Tanzania (TZ), United States (US).

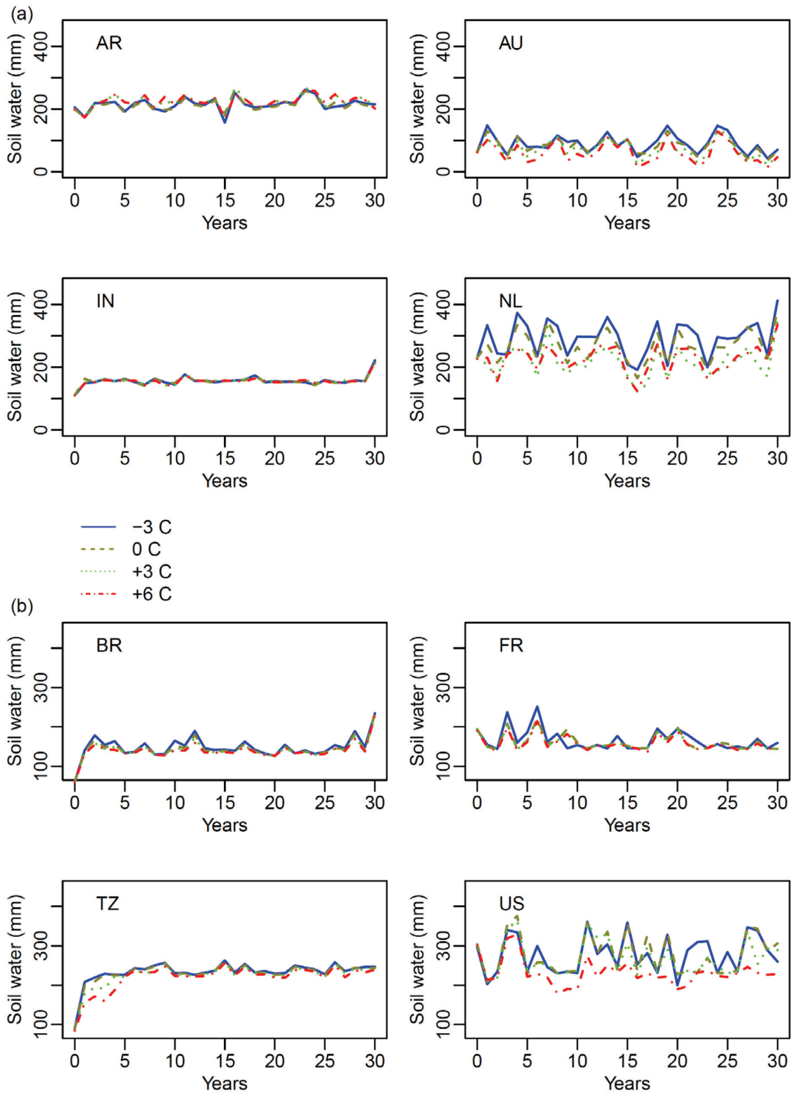

Figure S4.

Simulations of the plant available soil water at sowing for the different sites, temperatures and constant CO2 concentration (360 ppm). The lines represent the median of the model ensemble predictions for the site and scenario. The site abbreviations for wheat are: Argentina (AR), Australia (AU), India (IN); Netherlands (NL); for maize are: Brazil (BR), France (FR), Tanzania (TZ), United States (US).

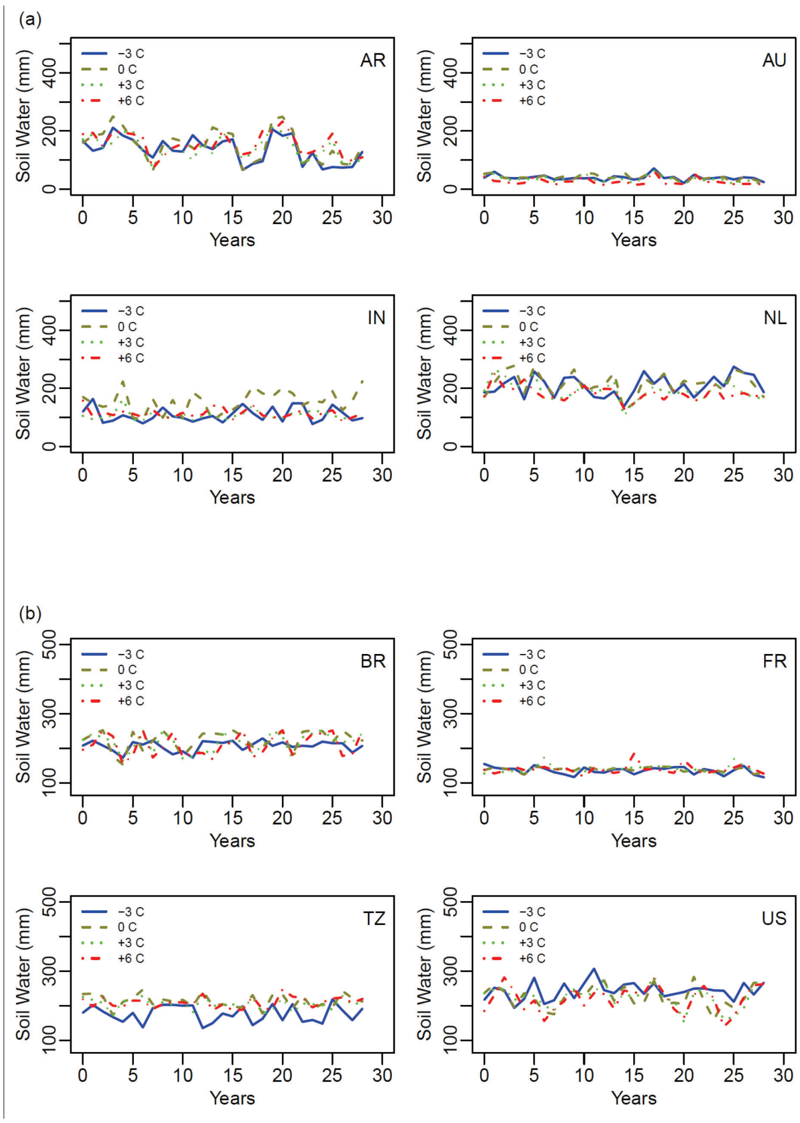

Figure S5.

Simulations of the plant available soil water at anthesis for the different sites, temperatures and constant CO2 concentration (360 ppm). The lines represent the median of the model ensemble predictions for the site and scenario. The site abbreviations for wheat are: Argentina (AR), Australia (AU), India (IN); Netherlands (NL); for maize are: Brazil (BR), France (FR), Tanzania (TZ), United States (US).

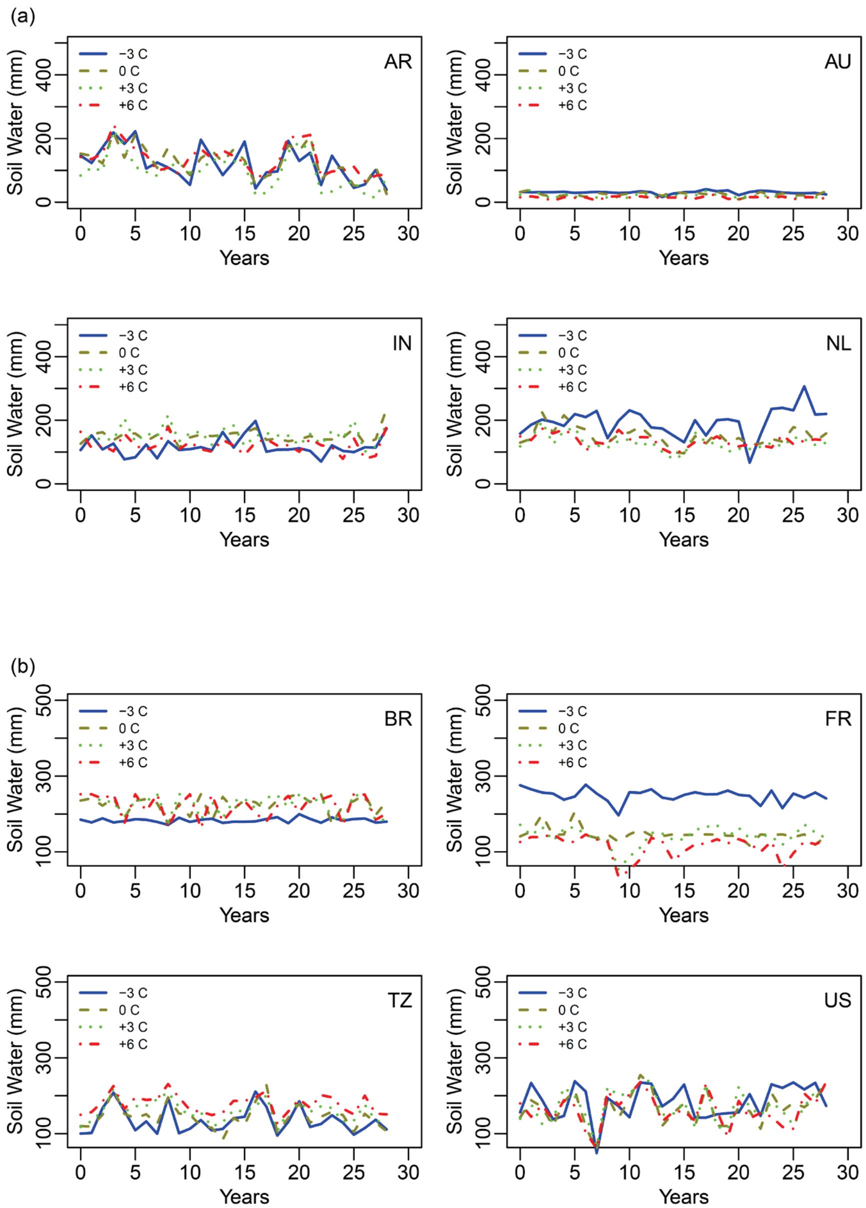

Figure S6.

Simulations of the plant available soil water at maturity for the different sites, temperatures and constant CO2 concentration (360 ppm). The lines represent the median of the model ensemble predictions for the site and scenario. The site abbreviations for wheat are: Argentina (AR), Australia (AU), India (IN); Netherlands (NL); for maize are: Brazil (BR), France (FR), Tanzania (TZ), United States (US).

Table S1.

Crop models used in the study.

Model (Version)	**Crop***	**Documentation (*Reference*)**
APSIM (V7.3)	M	http://www.apsim.info *(1)*
APSIM-NWheat (V1.55)	W	http://www.apsim.info/Wiki/ (2)
DayCent	W	http://www.nrel.colostate.edu/projects/daycent/ (3)
Ecosys	MW	https://portal.ales.ualberta.ca/ecosys/ (*4*)
MONICA (V1.0)	MW	http://monica.agrosystem-models.com (5)
SALUS	MW	http://salusmodel.glg.msu.edu (*6*)
STICS (V8.1)	MW	http://www6.paca.inra.fr/stics_eng/ (7)
Expert-N (V3.0.10) – SPASS (2.0)	W	http://www.helmholtz-muenchen.de/en/iboe/expertn/ (8)

*M, maize; W, wheat

Table S2.

Simulation scenarios.

Factors	**Factor levels**	**Maize**	**Wheat**
Site	4 sites across the globe	x	x
Temperature [°C]	Baseline, -3, +3, +6	x	x
CO_2 [ppm]	360, 540,	x	x
Simulation mode	Reinitialized, Continuous	x	x

Table S3.

Characteristics of the sites. Site name, crop (M=maize, W=wheat), latitude and longitude (Lat, Long), mean seasonal precipitation (Prec) and mean seasonal temperature (T) for the period 1980–2010, soil texture, lower limit of soil water (LL), drained upper limit (DUL), bulk density, rooting depth (Root D), soil organic carbon (SOC).

Site	Crop	Lat	Lon	P (mm)	T (°C)	Texture	LL (%v/v)	DUL (%v/v)	BD (g cm $^{-3}$)	Root D (cm)	Sowing date	Hybrid	Plant Den (plants m^{-2})	N Fert. (kg N ha^{-1})	Irrig. (mm)	SOC (mass%)
FR	M	46.25	0.07	378	17	Silt loam	15	32	1.13	120	26-Apr	Furio 9.5	9.5	255	377	0.9
US	M	42.01	-93.45	476	21	Loam	14	34	1.38	200	4-May	Golden Harvest GH-9014	7.5	167	0	2.4
BR	M	-17.52	-51.43	980	25	Clay	20	29	1.19	140	22-Oct	Pioneer 30K75	6.6	0	0	1.1
TZ	M	-6.5	37.39	258	27	Clay	35	51	1.22	130	26-Oct	TMV 1	9.5	61	178	1.4
NL	W	51.97	5.63	716	8.5	Silty clay loam	20	37	1.35	200	21-Oct	Arminda	228	160	0	2.4
AR	W	-37.5	-58.3	395	12	Clay loam	17	34	1.28	130	11-Aug	Oasis	239	120	0	2.7
IN	W	28.38	77.12	467	18.9	Sandy loam	12	19	1.55	160	24-Nov	HD 2009	250	120	383	0.4
AU	W	-30.89	116.72	246	16.2	Loamy sand	11	17	1.5	210	13-Jun	Gamenya	157	50	0	0.6

Table S4.

Relative changes of simulated yields (model ensemble) for the different sites and temperature levels under the *reinitialize*d mode (without the inclusion of SOC dynamics) compared to the baseline scenario.

Site \ Temp.	**-3°C**	**+3°C**	**+6°C**
AR	-11.04	-13.86	-36.46
AU	-15.01	2.50	-12.73
IN	-2.90	-19.16	-38.48
NL	-7.22	-20.32	-33.30
Avg. wheat	***-9.04***	***-12.71***	***-30.24***
BR	13.60	-16.45	-39.20
FR	-48.36	-6.58	-18.38
TZ	0.19	-20.38	-60.89
US	-19.74	-12.84	-29.48
Avg. maize	***-13.58***	***-14.06***	***-36.99***

Table S5

Relative changes of simulated yields (model ensemble) for the different sites and temperature level under the *continuous* mode (with the inclusion of SOC dynamics) compared to the baseline scenario.

Site \ Temp.	-3°C	+3°C	+6°C
AR	-7.40	-19.30	-34.93
AU	-29.65	-19.12	-41.08
IN	0.97	-22.01	-47.82
NL	0.09	-5.21	-16.86
Avg. wheat	***-9.00***	***-16.41***	***-35.17***
BR	-16.02	-5.51	-22.98
FR	-35.38	-13.4	-20.06
TZ	1.73	-38.98	-60.70
US	-3.47	-18.93	-25.23
Avg. maize	***-13.28***	***-19.21***	***-32.24***

Table S6.

Median changes in model output per degree of change in temperature. SOC, soil organic carbon; AR, Argentina; AU, Australia; IN, India; NL, Netherlands; BR, Brazil; FR, France; TZ, Tanzania; US, USA.

Site	**Δ Yield [ton ha^{-1} $°C^{-1}$]**	**Δ Transpiration [mm $°C^{-1}$]**	**Δ Soil N-NO_3^- [kgN ha^{-1} $°C^{-1}$]**	**Δ SOC [% $°C^{-1}$]**
AR	-0.28	-7.27	3.28	-3.56
AU	-0.08	-1.29	3.41	-0.69
IN	-0.21	-9.76	6.57	-0.83
NL	-0.26	-3.32	7.29	-4.41
BR	-0.18	-2.07	2.54	-0.22
FR	-0.15	-1.37	6.26	-1.15
TZ	-0.54	-8.10	9.01	-0.73
US	-0.31	-2.23	29.31	-1.64

Table S7.

Coefficient of variation of simulated yields (average yield between 1982-2010) for model ensemble across sites and temperature changes. AR, Argentina; AU, Australia; IN, India, NL, Netherlands; BR, Brazil; FR, France; TZ, Tanzania; US, USA.

Site	**Temperature change**			
	-3°C	**+0°C**	**+3°C**	**+6°C**
AR	47.30	39.37	37.72	68.22
AU	42.31	34.01	43.56	58.86
IN	47.83	33.69	36.17	36.69
NL	48.69	24.14	42.68	53.55
BR	98.15	46.38	44.42	39.62
FR	67.92	20.50	26.03	33.55
TZ	51.15	27.45	47.34	72.55
US	31.55	24.43	32.78	42.27

Table S8.

Value of the coefficients of the regression between average annual yield or crop residues [ton.ha^{-1}]) and temperature scenarios, SOC content and their interaction. [CO2] was kept at the baseline (360ppm). Significant differences compared to the null value were evaluated with a *t*-test and are indicated by the stars ('*': significantly different; '**': highly significantly different, '***': very highly significantly different).

Variable	**System**	**c_0**	**c_1 (T)**	**c_2 (SOC)**	**c_3 (T*SOC)**
Avg. An. Yield	Wheat	1.77***	-0.14***	1.87***	0.06***
[ton.ha^{-1}]	Maize	4.32***	0.03	1.74***	-0.07
Avg. An. Res.	Wheat	2.35***	-0.27***	2.24***	0.31***
[ton.ha^{-1}]	Maize	6.84***	-0.36***	0.68**	0.01

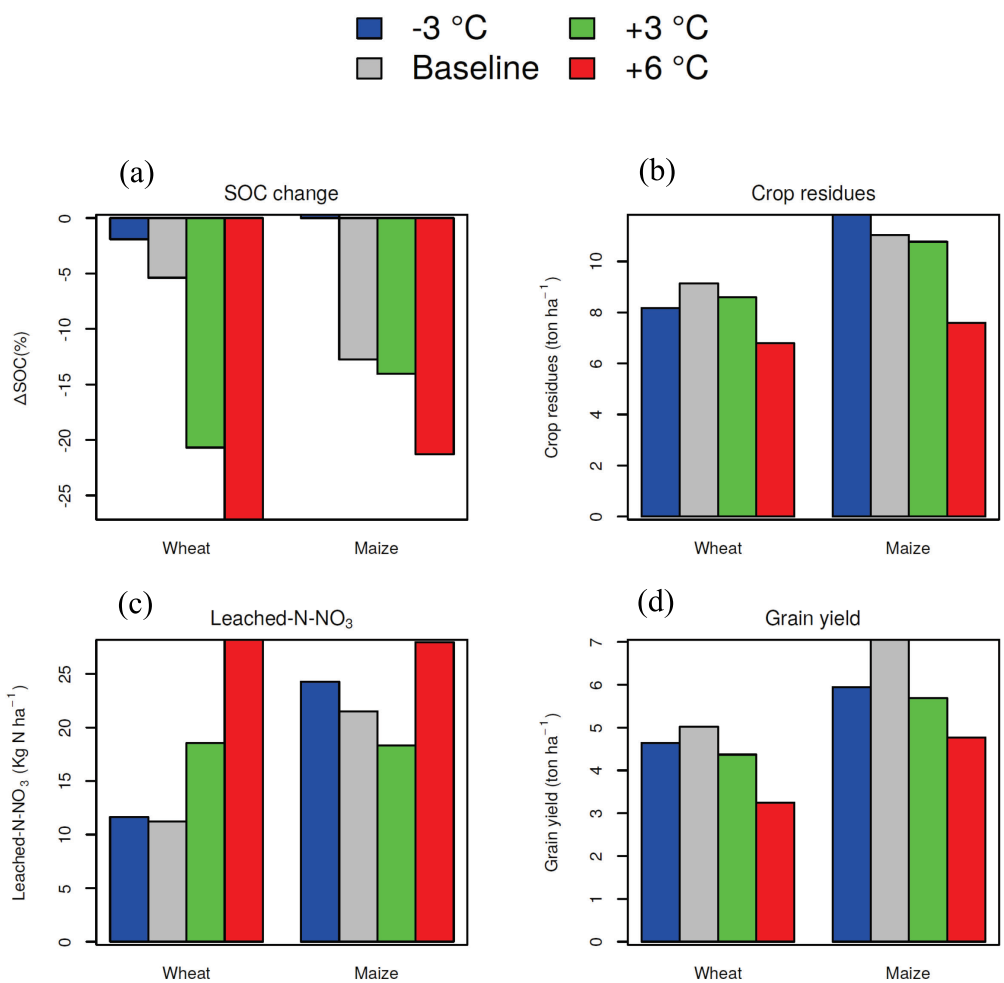

Figure S7.

The figure shows the influence of temperature increase on several response variables for the wheat- and maize-fallow cropping systems. The response variables are: relative SOC content change over 30 (a), residues amount returned to the field (b), nitrate leaching at harvest from the portion of the soil comprised between the top of the soil and the rooting depth (c), and average annual yield (d) .

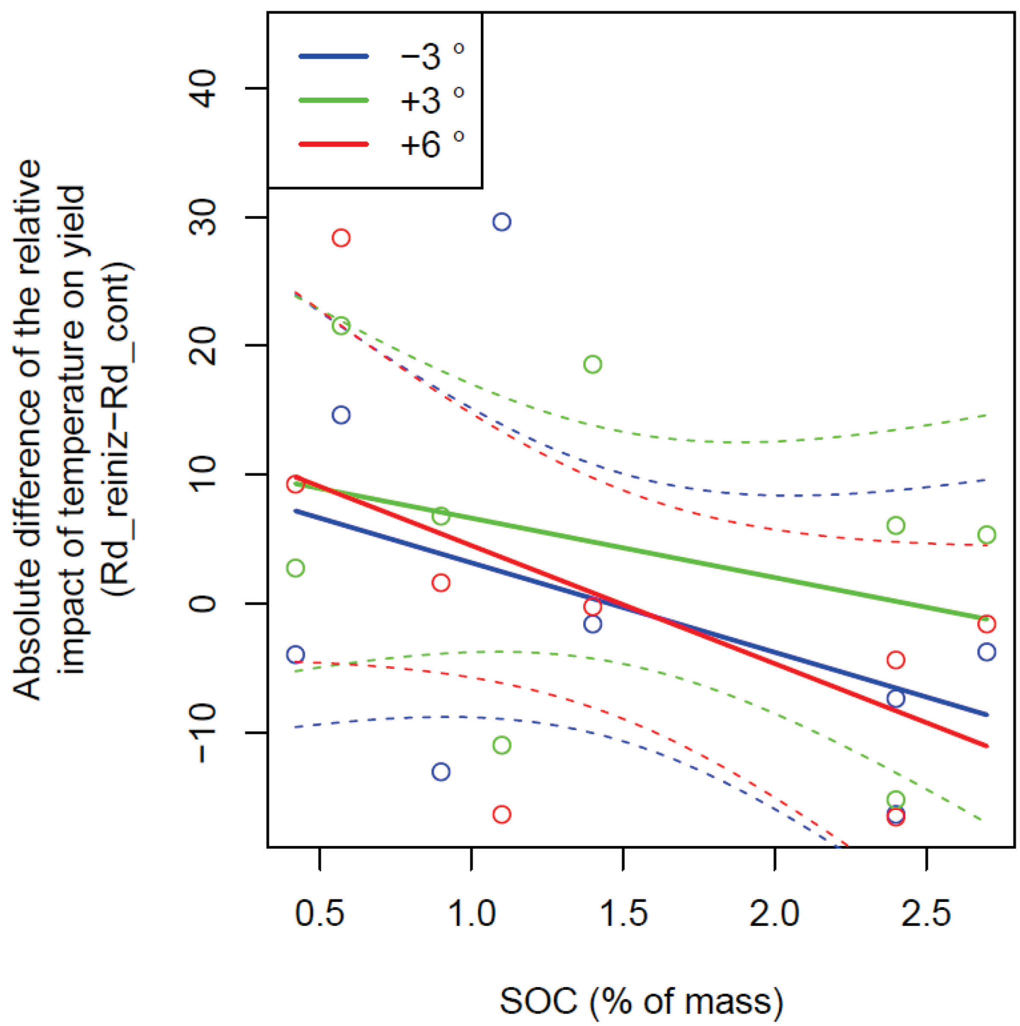

Figure S8.

Correlation between soil organic carbon at the beginning of the simulation and the interaction of SOC decline – increase in temperature. We calculated the interaction SOC decline – increase in temperature as the difference between the relative changes of simulated yields between future climate scenarios and the baseline scenarios in the reinitialized models simulations (Figure S4.) and in the continuous models simulations.

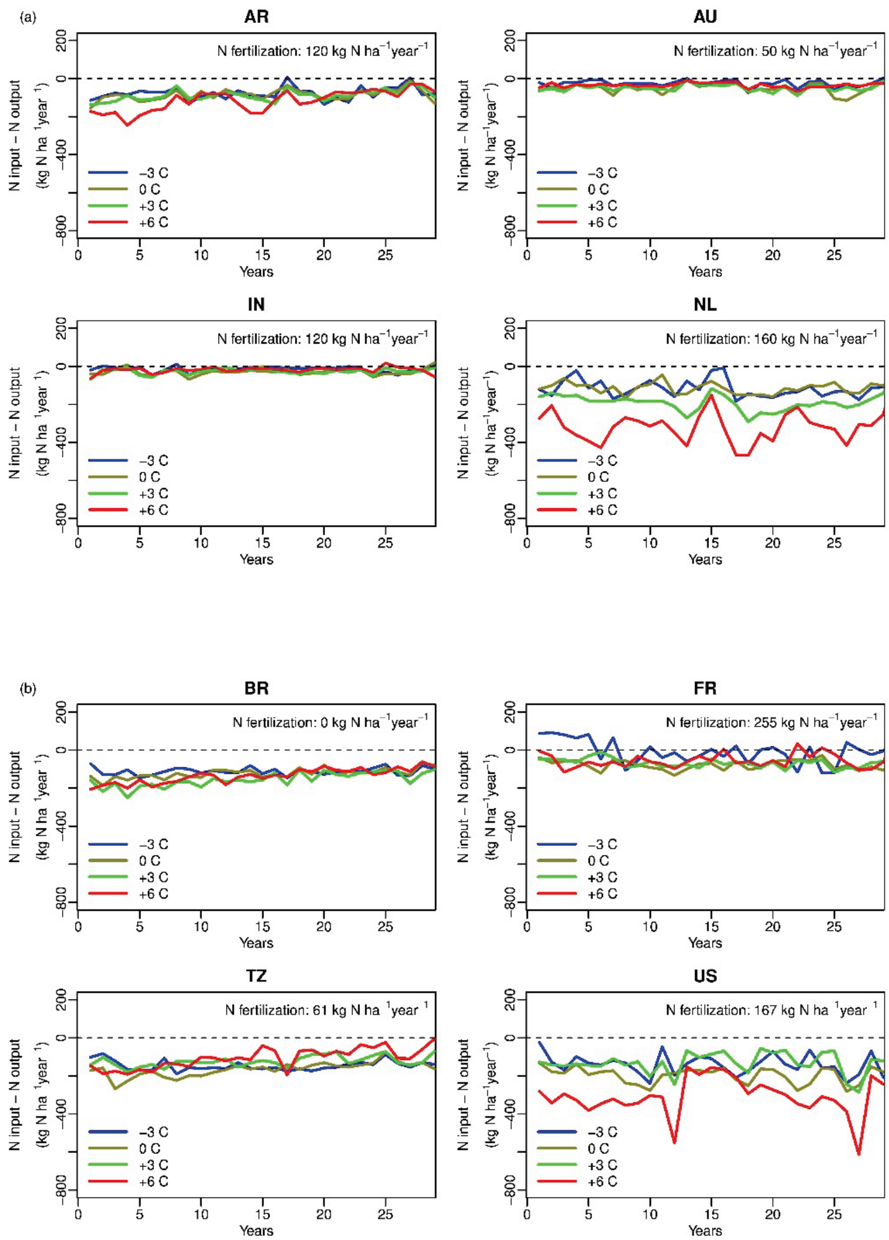

Figure S9.

Average annual difference between N input (mineral N fertilizer, N from crop residues minus N leaching at harvest, N unused at harvest, N uptake from grain and biomass) for each wheat and maize site under different temperatures at [CO_2] 360pmm.

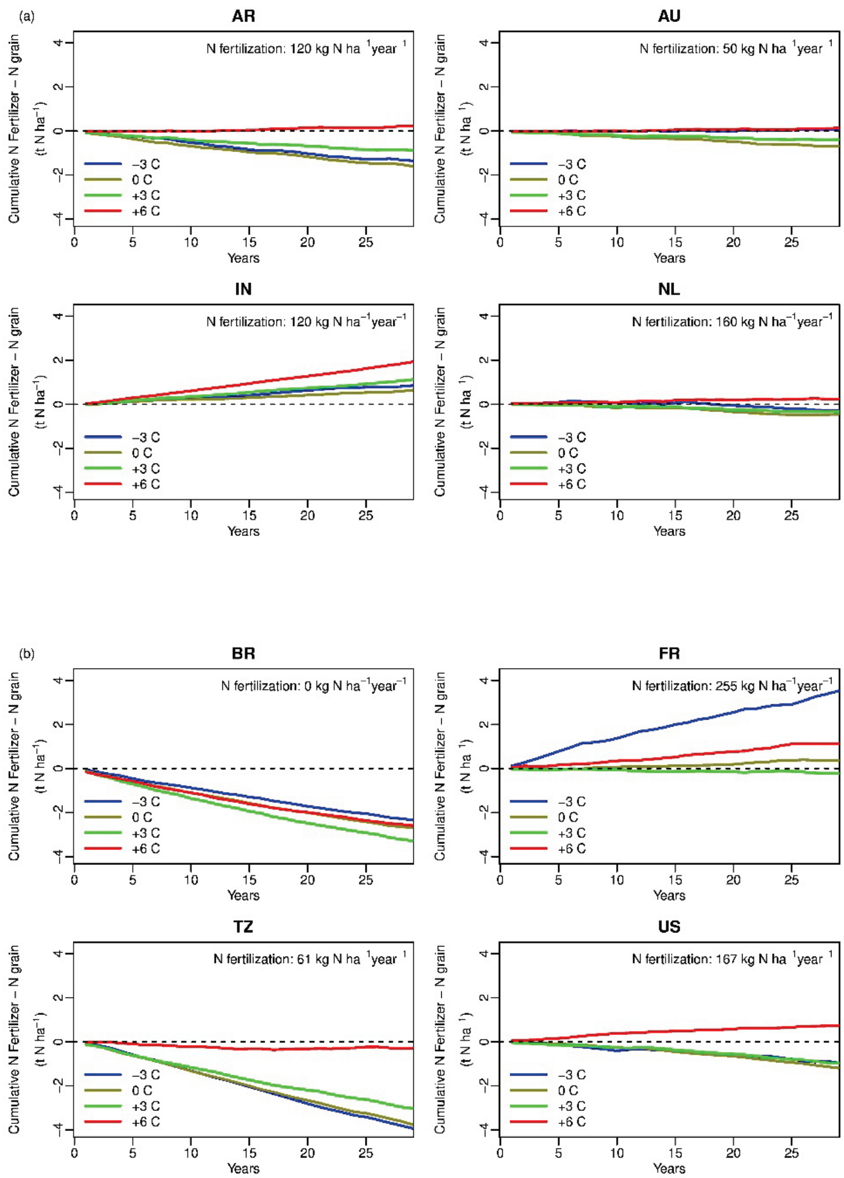

Figure S10.

Cumulative annual difference between N added as fertilizer and N in the harvested grain (estimated as 2% of the yield) for each wheat and maize site under different temperatures at $[CO_2]$ 360pmm.

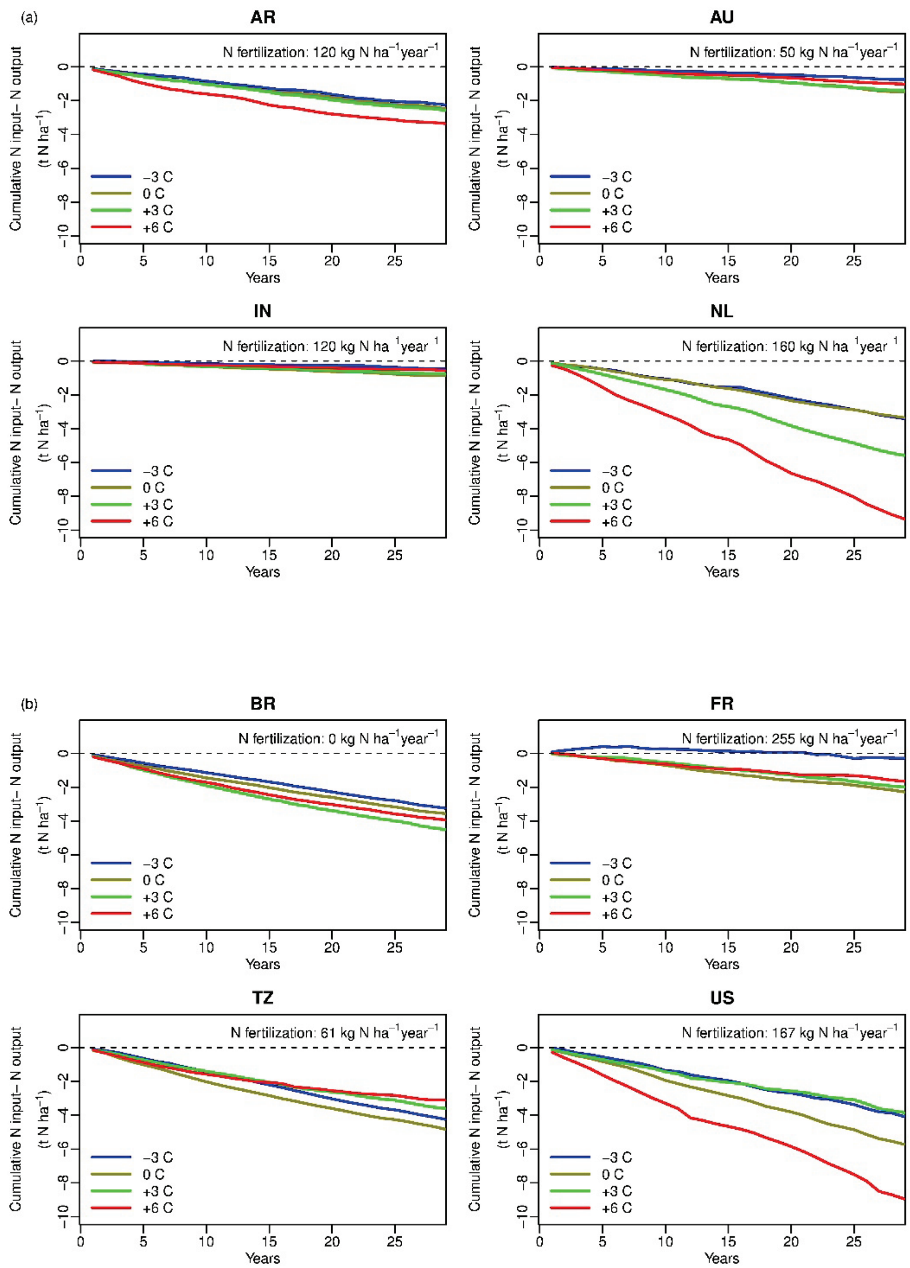

Figure S 11: The figure shows the cumulative difference between N input (mineral N fertilizer, N from crop residues) minus and N removed (N leaching at harvest, N unused at harvest, N uptake from grain and biomass) for each wheat and maize site under different temperatures at [CO2] 360pmm [CO2].

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