Supplement of:

The role of cover crops for cropland soil carbon, nitrogen leaching, and agricultural yields - A global simulation study with LPJmL (V. 5.0-tillage-cc)

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Supplement content:

S1 Supplementary information to methods and data

S1.1 General model functions in LPJmL5.0-tillage-cc

In the model three litter layers and five hydrologically active soil layers of differing thickness to a total depth of three meter are distinguished. Each soil layer has its specific temperature and moisture levels, affecting the decomposition rates of soil organic matter, represented in the model by fast and slow decomposing (30 and 1000 years turnover time, respectively) C and N pools (Lutz et al., 2019; Schaphoff et al., 2018). Carbon and N pools of represented vegetation, litter, and soil layers are updated daily. Biomass formation is represented by a simplified version of photosynthesis according to Farquhar et al. (1980). The phenology of tree and grass plant functional types (PFTs) of the represented natural vegetation are based on Jolly et al. (2005) with modification of the growing season index as described in Forkel et al. (2014). Crop functional types (CFTs, see Table S1.1) representing the vegetation on managed land are parameterized with specific temperature and phenological heat unit requirements for growth (Müller et al., 2017). Cropland irrigation was mechanistically simulated by either surface flooding, sprinkler, or drip irrigation, here setting one type per country (Jägermeyr et al., 2015; Rohwer et al., 2007). We used the potential irrigation setting to simulate irrigated cropping systems (for cropland areas equipped for irrigation as informed by the input data, see Sect. S1.2) to account for missing representation of ground water sourcing, when this model version only considers surface water withdrawal amounts, in the case of alternatively setting to limited irrigation.

During simulated main crop growing seasons, manure (C to N ratio of applied manure was assumed to be 14.5 to 1) was applied at the first scheduled mineral N fertilization event of a growing crop (CFT). Half of the N contained in the manure was assumed as ammonium (NH_4) and added to the pool of the upper soil layer, whereas the entire C and the remaining N (assumed as organic share), were transferred to the respective litter pools. Conventional tillage was assumed as the default soil management on all cropland, applied when converting land to cropland, as well as at main crop seeding and harvest events. The tillage routine submerges and transfers 95 % of the surface biomass remaining on-site, to the incorporated soil litter pools. In the model, tillage mostly affects processes in the first soil layer up to 20 cm depth (Lutz et al., 2019). In the case of no-tillage, the remaining aboveground biomass of the main crops' residues left on the field after harvest are added to the surface soil litter pools, representing mulching practices.

Table S1.1 Crop functional types (CFTs) in LPJml5.0-tillage-cc and included in the study

CFT	Simulated as
temperate cereals	wheat
rice	rice
tropical cereals	millet
pulses	field peas
temperate roots	sugar beet
tropical roots	cassava
maize	maize
sunflower	sunflower
soybean	soybean
groundnuts	groundnuts

CFT	Simulated as
rapeseed	rapeseed
sugarcane	sugarcane
others	maize in tropical and wheat in temperate regions
managed grass	managed temperate C3, polar C3, and tropical C4 grass (outputs not considered here)
bioenergy grass	not simulated here
bioenergy trees	not simulated here
cover crop	temperate C3, polar C3, and tropical C4 grass with daily allocation

S1.2 Model input data

For the simulations of this study, the model was driven with monthly mean temperature input data from the Climate Research Unit (CRU TS version 3.23, University of East Anglia Climate Research Unit, 2015; Harris et al. (2014)). Monthly precipitation and number of wet days data was from the Global Precipitation Climatology Centre (GPCC Full Data Reanalysis version 7.0; Becker et al. (2013)). The monthly radiation data (shortwave and net longwave downward) was taken from the ERA-Interim data set (Dee et al., 2011). Soil texture classes remained static over the simulation period and were based on the Harmonized World Soil Database (Nachtergaele et al., 2009) and soil-pH was taken from the WISE data set (Batjes, 2006). Annual atmospheric CO_2-concentration input data were based on the NOAA/ESRL Mauna Loa station (Tans and Keeling, 2015) reports, and natural N deposition data on the ACCMIP database (Lamarque et al., 2013).

Model input data on historical land use, distinguishing shares of irrigated and rainfed crop-group specific physical cropland (years 850-2015), as well as mineral N fertilizer application rates (years 1900-2015), were based on LUH2v2 data by Hurtt et al. (2020). The original data per crop group were (dis-)aggregated and remapped, using the MADRaT tool (Dietrich et al., 2020), to match the CFTs of LPJmL (Table S1.1) and the here targeted simulation unit of 0.5 degree grid cell resolution (~50 km x 50 km at the equator). In the year 2010 there were 1,502,674,969 ha total physical cropland (Fig. S1.2 for maps of physical cropland and mineral N fertilizer application rates).

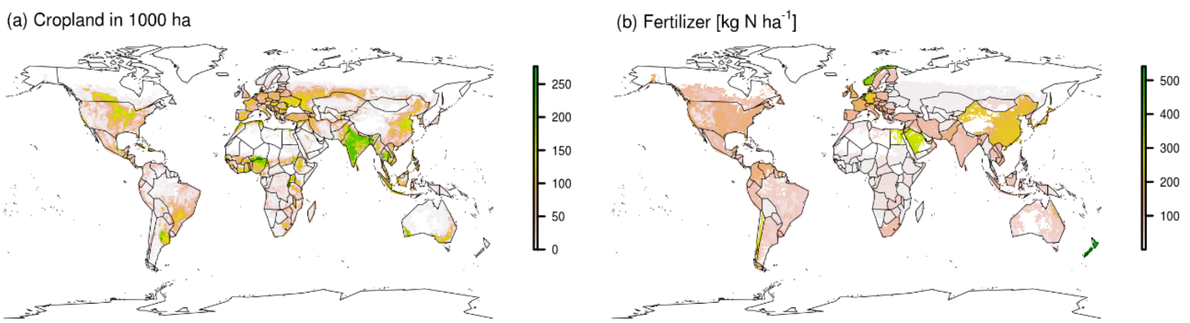

Figure S1.2 Maps depict the spatial pattern of the model input data used in the process based simulations and for post-processing model outputs: (a) Physical cropland in 1000 hectares per grid cell and (b) Mineral N fertilizer application rate in kg N ha^{-1} for the year 2010, based on LUH2v2 (Hurtt et al., 2020) physical cropland distribution data.

Sowing date and phenological heat units were prescribed with a growing season input data set based on Portmann et al. (2010) and Sacks et al. (2010), described by Elliott et al. (2015). The historical manure input data (years 1860-2014) was based on the time series of N contained in manure applied on cropland by Zhang et al. (2017). The residue input data set (years 1850-2015) prescribed the fraction of residue biomass remaining on the field after harvest of the main crop. It was generated, by setting residue recycling shares to values per CFT-group (i.e., cereals, fibrous, non-fibrous, and others), which were obtained from (Dietrich et al., 2020) and based on national reported cropland data retrieved from FAOSTAT accounting for historical main crop residue removal rates associated to land management practices, as burning on field, as well as to secondary off-field usages, as household burning, and livestock fodder.

S1.3 Overview simulation setup for cover crop and tillage scenarios

Table S1.3 Spin-up and soil management scenario modeling protocol using LPJml5.0-tillage-cc

Simulation step	Number of years	Start year	End year	Year restart written	Land use and other management	Tillage setting	Soil cover off-season cropland
1. Spin-up:							
1.1. Potential natural vegetation	7000	(-)5101	1900	1900	-	-	-
1.2. Land use	451	1511	1961	1961	static 2010	tillage	bare fallow
2. Management scenarios:							
2. 1. Baseline (REF)	50	1962	2011	-	static 2010	tillage	bare fallow
2.2. Cover crops (CC)	50	1962	2011	-	static 2010	tillage	cover crops
2.3. Cover crops with no-tillage (CCNT)	50	1962	2011	-	static 2010	no-tillage	cover crops
2.4. No-tillage (NT)	50	1962	2011	-	static 2010	no-tillage	bare fallow

S1.4 Conservation Agriculture cropland area time series data (1974-2010)

We applied a time series of the global annual CA cropland area per grid cell covering the years 1974-2010 (Fig. S1.4). This data set was obtained combining data of the historical land use and physical cropland used as model input (Sect. S1.2), field size (Fritz et al., 2015) (year ~2005), water erosion (Nachtergaele et al., 2011) (year 2000), aridity index (FAO, 2015) (averaged for years 1965-1990), Gross National Income time series (World Bank, 2017) (years 1987-2010), and national reported CA cropland area for the years 1974-2010 (FAO, 2016). Input data to this time series were recycled as static value per grid cell with considered cropland, if available only for one time slice or else adjusted for the coverage of the entire CA area reporting period, the physical cropland data, and resolution. In the case of missing national reported annual CA area values, these were interpreted as zero, if outside reporting periods, or gaps filled with the last reported value, if within. National reported Conservation Agriculture area data were downscaled to the grid scale physical cropland distribution following methods described in Porwollik et al. (2019). Historical annual shares of reported and mapped Conservation Agriculture area on global cropland rose from 0.02 % in the year 1974 to 10 % in 2010 (FAO, 2016). During this period largest increases of CA area were reported for cropland in Northern and South America, but also for Australia, New Zealand, and Kazakhstan. For Africa and Asia adoption rates of CA practices were rather low (Kassam et al., 2018; Porwollik et al., 2019; Prestele et al., 2018). This CA cropland time series data as well has been included in Herzfeld et al. (2021) and Karstens et al. (2020), quantifying soil C responses to historical land-use change dynamics and land management practices, including tillage practices and sensitivity to crop residue removal rates.

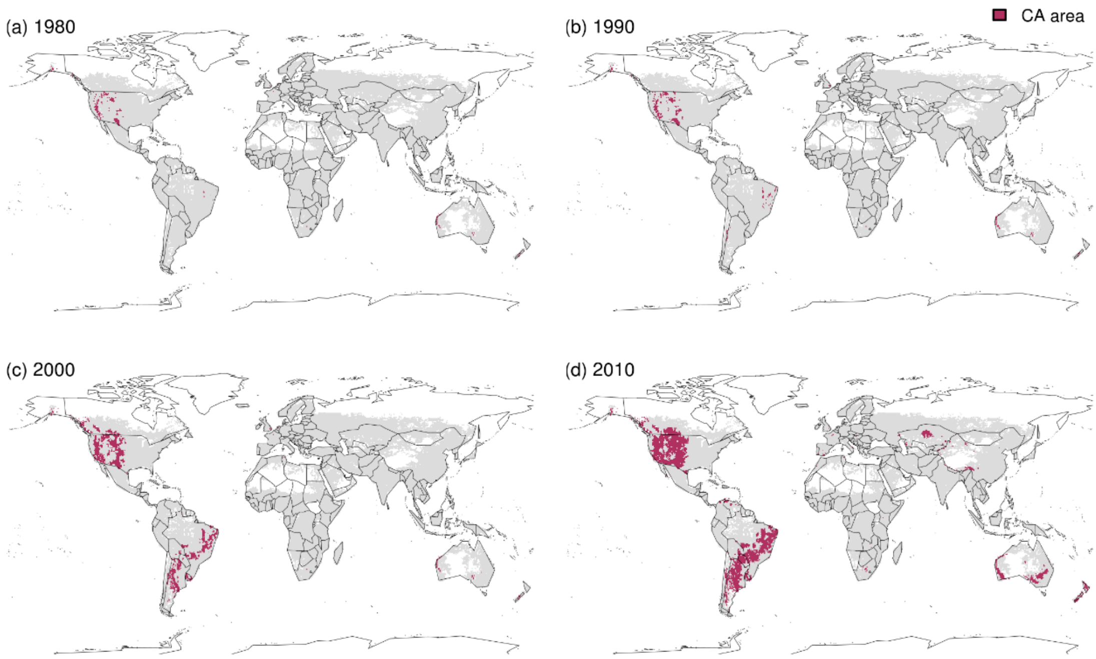

Figure S1.4 Maps (a-d) of global cropland mapped with Conservation Agriculture area (purple) and conventional tillage practices (grey) per grid cell showing time slices of the gridded time series data applied in this study for the years: 1980, 1990, 2000, and 2010, respectively, (white as no cropland).

S2 Supplementary information to management results

S2.1 Simulated responses to cover crop and tillage practices in comparison to values found in the literature

Table S2.1 Responses to cover crops (CC) in comparison to the control simulation with bare soil fallow (REF) on cropland during off-season between consecutive primary crop growing seasons, both with conventional tillage for soil C sequestration rate, as well as changes of N leaching rate and following main crop productivity in comparison to other studies' findings (see Sect. 2.3 for equations used). The time period indicated in the first column depicts the number of years since introduction of the cover crop practice as well as the management duration. The time period indicated for a value found in the literature correspond to the time frame of LPJml5.0-tillage-cc model outputs used to generate global area-weighted median (Q1, Q3) changes as provided in the second column of the table.

Time period (years)	Simulated ΔCC median (quartiles)	Literature estimate	Unit per hectare per year	Literature type	Literature source
Soil carbon sequestration rate (Eq. 1)					
12 - 50	0.55 (0.26, 0.88)	0.01 - 0.46	t C ha^{-1} yr^{-1}	Report	Paulsen (2020), range of annual soil C sequestration rates by CC citing Poeplau and Don (2015) and two other experimental studies' results, summarized as: 0.1 to 0.46 for topsoil (0-15 cm depth) and 0.01 to 0.32 t C ha^{-1} yr^{-1} subsoil (15-75 cm depth), originally report in kg C ha^{-1} yr^{-1}
20 - 50	0.53 (0.25, 0.84)	0.05 - 0.25	t C ha^{-1} yr^{-1}	Review	Lal (2004), range of annual soil C sequestration rates by CC, value from their Fig. 2, unit originally reported in kg C ha^{-1} yr^{-1}
25 - 50	0.52 (0.24, 0.82)	0.05 - 0.5	t C ha^{-1} yr^{-1}	Review	Stockmann et al. (2013), range of potential annual soil C sequestration rates by CC per climatic region based on Lal (2008), depth not indicated, also cited in Olin et al. (2015) cover crop simulation for 1.5 m soil depth stating maximum C sequestration rate in tropical humid region of 0.08 and over time diminishing to 0.01 kg C m^{-2} yr^{-1}
1 - 50	0.55 (0.22, 0.90)	0.125, 0.258, 0.515	t C ha^{-1} yr^{-1}	Simulation	Sommer and Bossio (2014), annual soil C sequestration rates for

Time period (years)	Simulated ΔCC median (quartiles)	Literature estimate	Unit per hectare per year	Literature type	Literature source
					simulations of 'improved arable land management practices' for 0-25 cm depth, total potential 32-64 PgC soil C accumulation on agricultural land after 87 years of CC globally, 0.37 (0.74) PgC yr^{-1} C in their low (high) input scenarios as average annual C sequestration rates over the first 50 years, in their functions assuming 13.3 (26.2) Mg C ha^{-1} cumulative C sequestration after 87 years in their low (high) scenarios, respectively
1 - 50	0.55 (0.22, 0.90)	0.32 ± 0.08	t C ha^{-1} yr^{-1}	Meta-analysis	Poeplau and Don (2015), value for mean ± SD annual C sequestration rate, mean total SOC stock change of 16.7 ± 1.5 Mg C ha^{-1} in the upper 22 cm soil depth for 1-54 years
1 - 50	0.55 (0.22, 0.90)	0.56	t C ha^{-1} yr^{-1}	Meta-analysis	Jian et al. (2020), value stated as mean rate of carbon sequestration from cover cropping across all studies reported originally in Mg C ha^{-1} yr^{-1}; based on 5,241 data entries from 281 published studies, no indication of duration
Change nitrogen leaching rates (Eq. 2)					
1 - 17	-46 (-68, -13)	-50 (-61, -37)	%	Meta-analysis	Thapa et al. (2018), value for CC grasses (99 % Confidence Interval (CI)), including data of Tonitto et al. (2006) below
2 - 7	-39 (-61, -8)	-50 (-60, -40)	%	Meta-analysis	Valkama et al. (2015), value as average reduced N leaching loss (95 % CI) for grasses as mainly non-leguminous CC, them also citing Quemada et al. (2013) for Southern European and USA studies meta-analysis for non-leguminous CC

Time period (years)	Simulated ΔCC median (quartiles)	Literature estimate	Unit per hectare per year	Literature type	Literature source
					effect in irrigated systems as well reporting 50 % per year as annual average across experiments and durations
2 - 3	-10 (-36, -1)	-70	%	Meta-analysis	Tonitto et al. (2006), values as mean, 95 % CI guessed from their Fig. 7 about -78 to -62 %
Change yield maize (Eq. 2)					
1 - 50	-0.9 (-11, 0.4)	1 (0.99, 1.02)	%	Meta-analysis	Marcillo and Miguez (2017), update of a former meta-analysis on corn yields with grass cover crops, for US and Canada, for publications on experiments between years 1965-2015 but no indication for duration found, these authors find neutral to positive effects but no significant differences, value as weighted mean (95 % CI) response ratio (yield with CC to yield without CC)
1 - 5	0 (-1, 0)	1.3 - 9.6	%	National statistic	SARE (2019), report with data from National Cover Crop surveys conducted annually for crop years 2012-2016 in USA, range of annual changes for corn yield with CC compared to without
Change yield soybean (Eq. 2)					
1 - 5	0 (0, 0.3)	2.8 - 11.6	%	National statistic	SARE (2019), report with data from National Cover Crop surveys conducted annually for crop years 2012-2016, range of annual changes for soybean yield with CC compared to without
Change average yield as mean across median changes of the four crops					
1 - 28	-2.1	-4	%	Meta-analysis	Abdalla et al. (2019), meta-analysis on CC for n=102 of total 158 for non-legumes effects

Time period (years)	Simulated ΔCC median (quartiles)	Literature estimate	Unit per hectare per year	Literature type	Literature source
1 - 17	-2	not significantly different	%	Meta-analysis	Thapa et al. (2018), non-legumes CC effect on yields of different following main crop types, including data of Tonitto et al. (2006)
2 - 7	-1.5	-3	%	Meta-analysis	Valkama et al. (2015), for 'Nordic countries' as Denmark, Sweden Finland, Norway, on CC for spring cereals
2 - 3	-0.1	-3	%	Meta-analysis	Tonitto et al. (2006), non-legume CC effect on corn, sorghum, and vegetables experiments, USA and Canada, decline found not statistically significant

S2.2 Soil N immobilization rate and gross N mineralization rate with management duration

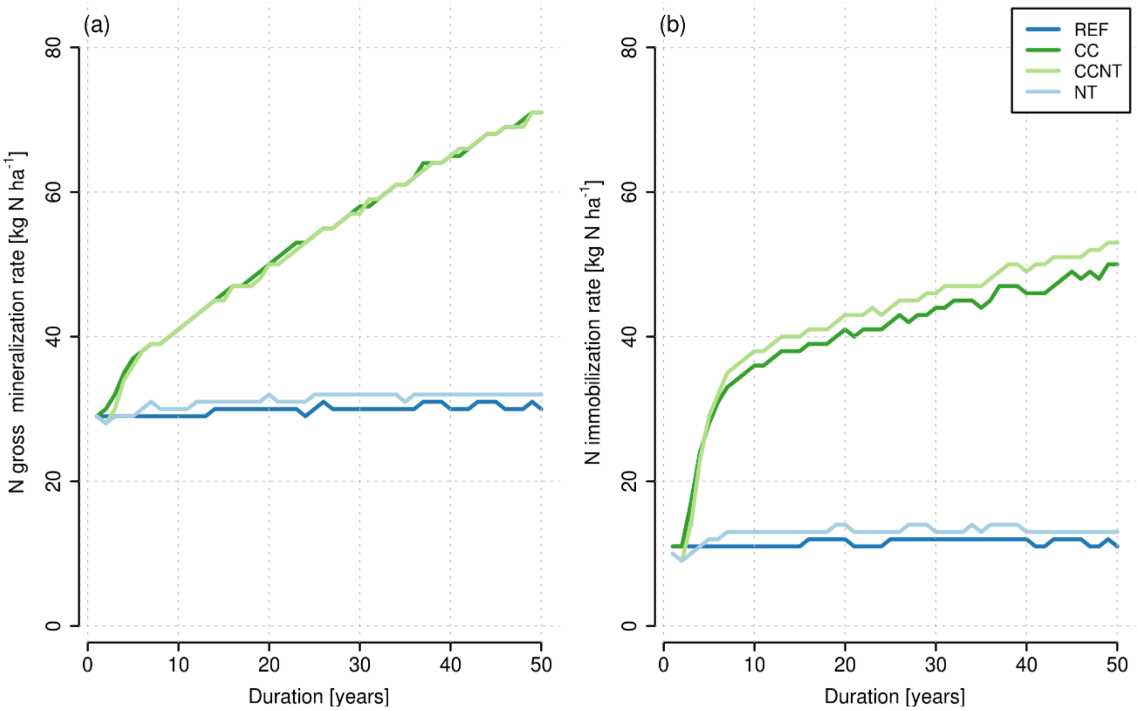

Figure SI2.2 Global annual spatial aggregated area-weighted median: (a) Gross N mineralization rates and b) N immobilization rates for global cropland soils during the 50 year simulation period as lines for each simulated management scenario (REF, CC, CCNT, and NT).

S2.3 Spatial pattern of changes in soil C and N leaching rate due to cover crop management

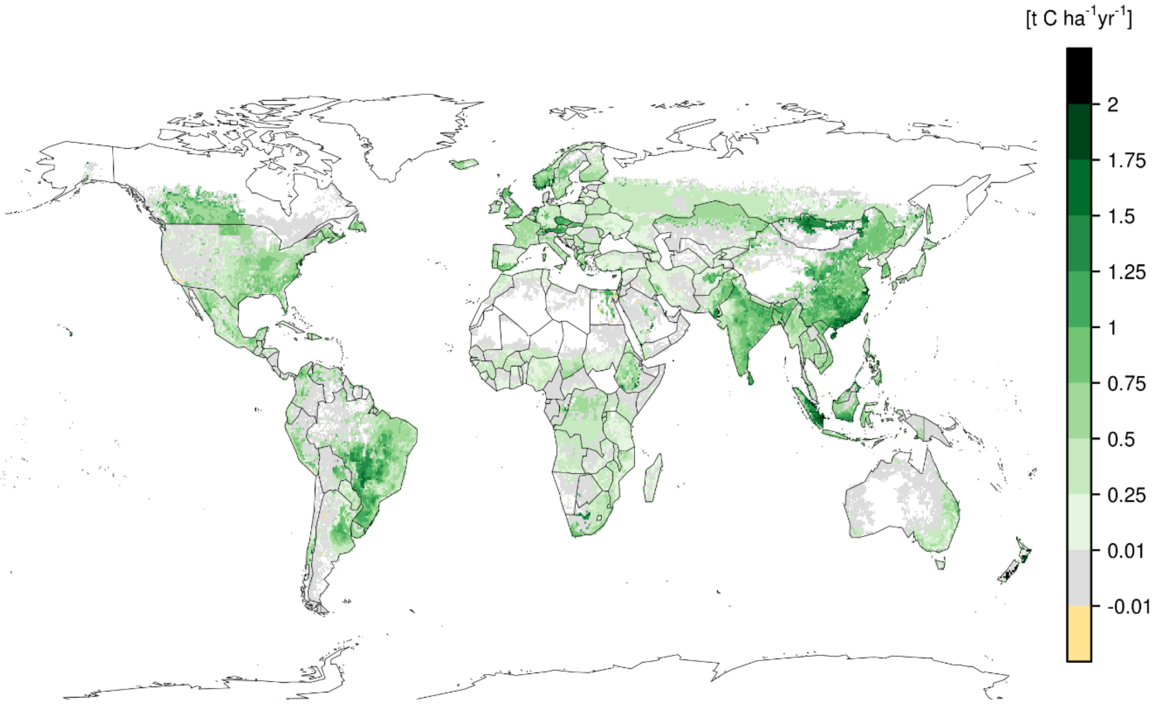

Figure S2.3.1 Map of average annual soil carbon sequestration rates in t C ha^{-1} yr^{-1} with cover crops (CC), as absolute difference to the soil carbon stock in the control with bare fallow (REF) divided by the management duration (Eq. 1), per cropland hectare and grid cell in the 50th year of the simulation period (white as no cropland).

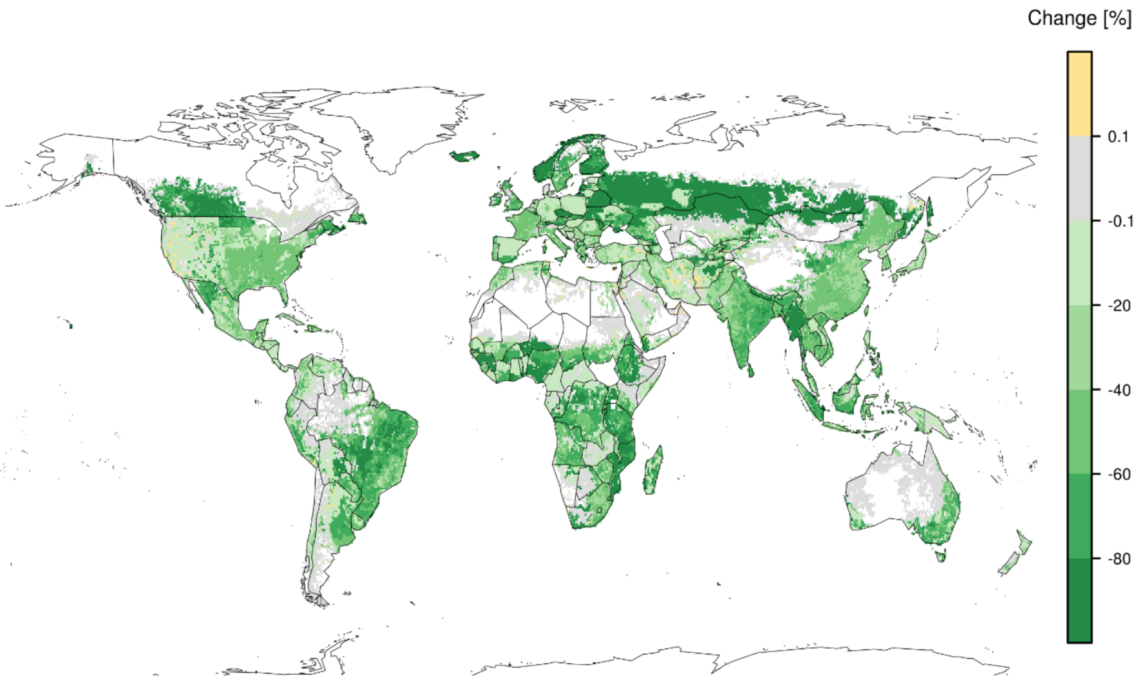

Figure S2.3.2 Map displays the changes of soil N leaching rates from cropland as annual median relative difference in percent (%) per hectare and grid cell due to cover crops (CC) relative to the control with bare fallow (REF) for the 50 year simulation period.

S2.4 Boxplots of changes for rainfed and irrigated crop productivity due to altered management

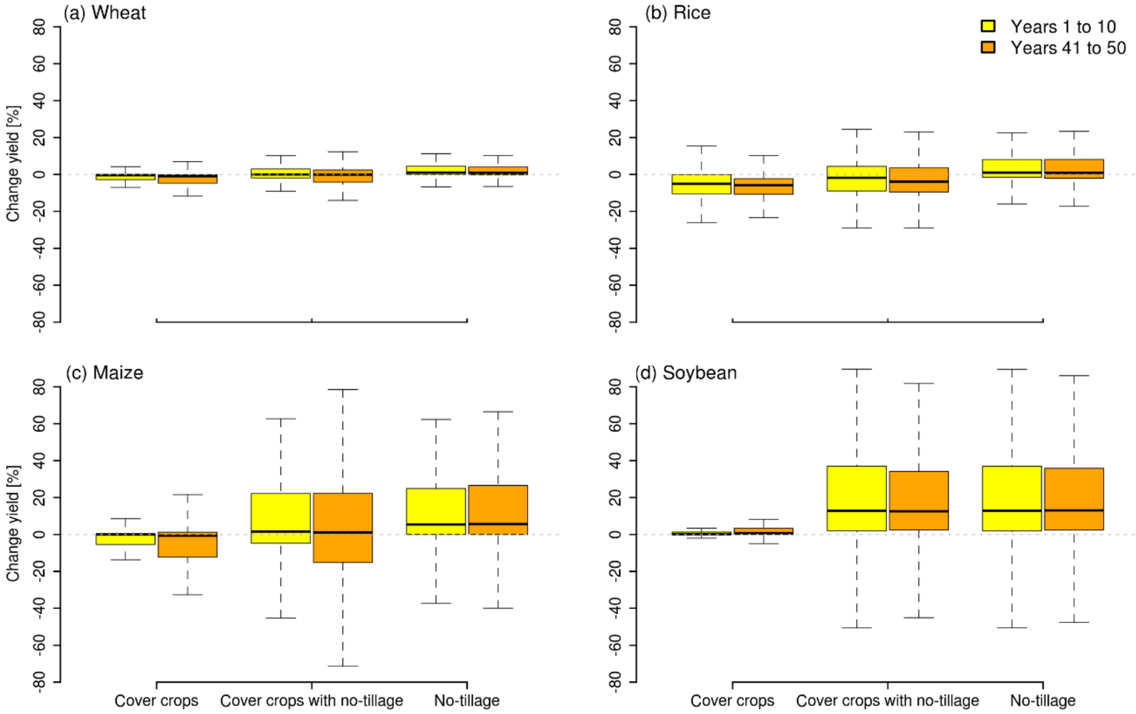

Figure S2.4.1 Panels (a-d) displaying changes in rainfed wheat, rice, maize, and soybean yield as boxplots of relative differences in percent (%) area-weighted by crop-specific physical cropland, due to alternative management practices (CC, CCNT, and NT) compared to the baseline (REF) for the first (left bars, yellow) and last decades (right bars, orange) of the 50 year simulation period. Boxes' black midlines indicate the spatial median across the distribution of responses, the lower and upper edges of the boxes the first and third quartiles, and whiskers extending both to the minimum and maximum values within 1.5 times the interquartile range, respectively from each Q1 and Q3 (outliers, defined as values outside this range are not shown here).

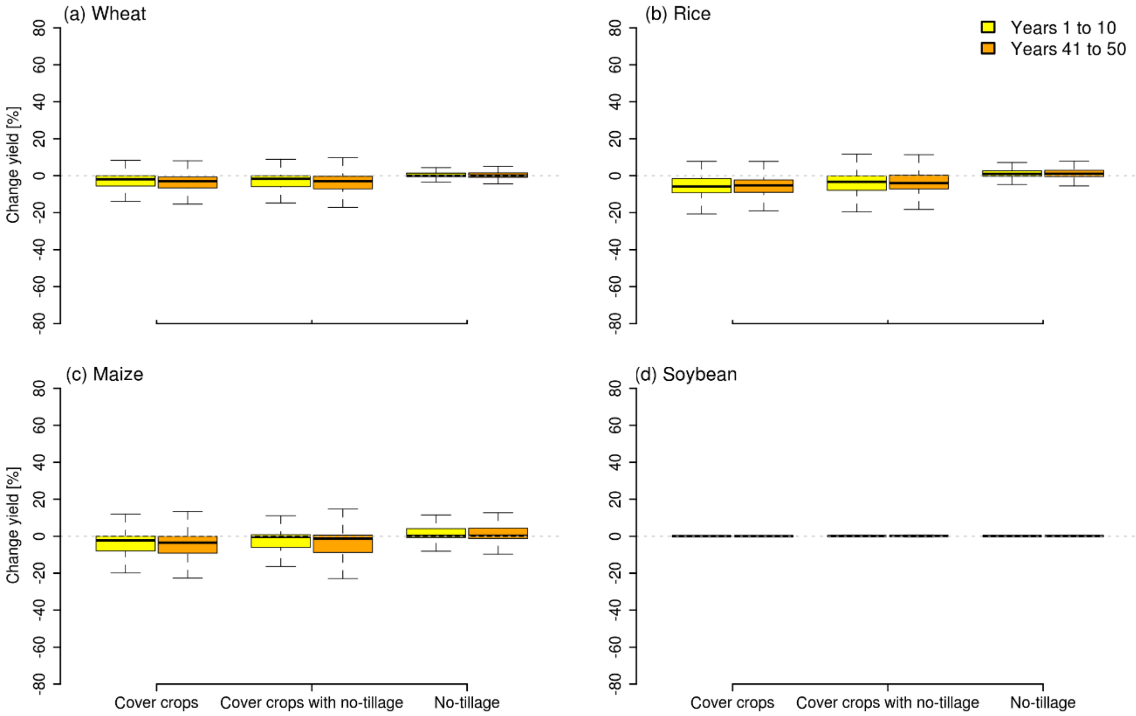

Figure S2.4.2 Panels (a-d) displaying changes in irrigated wheat, rice, maize, and soybean yield as boxplots of relative differences in percent (%) area-weighted by crop-specific physical cropland, due to alternative management practices (CC, CCNT, and NT) compared to the baseline (REF) for the first (left bars, yellow) and last decades (right bars, orange) of the 50 year simulation period. Boxes' black midlines indicate the spatial median across the distribution of responses, the lower and upper edges of the boxes the first and third quartiles, and whiskers extending both to the minimum and maximum values within 1.5 times the interquartile range, respectively from each Q1 and Q3 (outliers, defined as values outside this range are not shown here). Irrigated shares of total global crop type specific physical cropland area were 16 % for wheat, 12 % for maize, 35 % for rice, and 11 % for soybean based on land use model input data described in Sect. S1.2.

S2.5 Spatial pattern of productivity changes due to cover crop practices combined with no-tillage

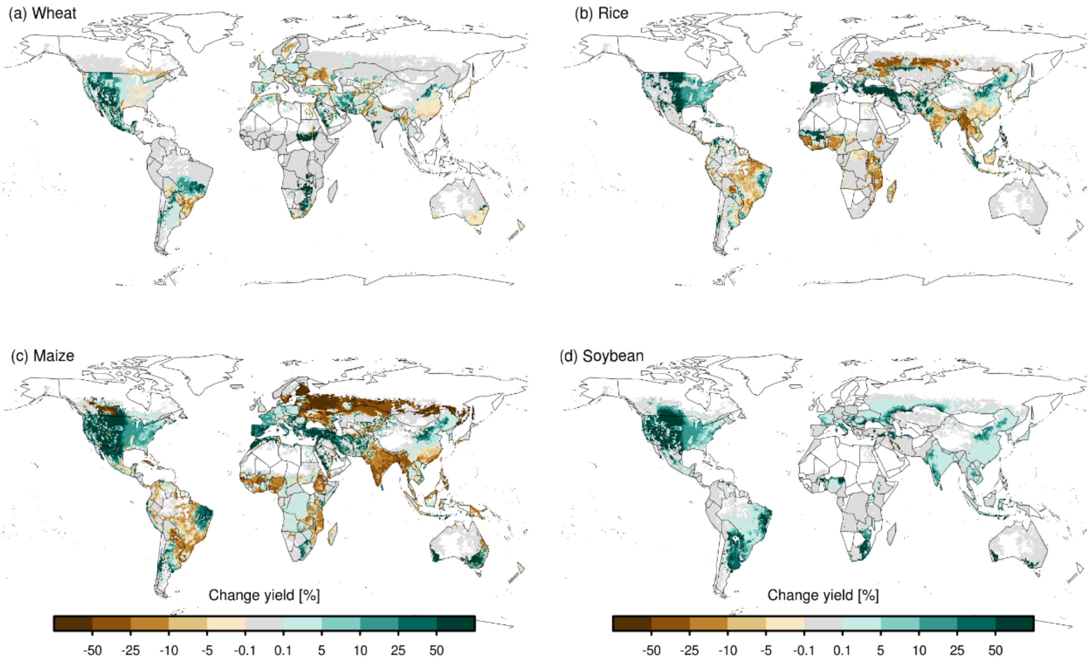

Figure S2.5 Maps showing changes of crop productivity in response to cover crop practices combined with no-tillage (CCNT) compared to the baseline with conventional tillage and bare fallow on cropland area during main crop off-season periods (REF) as annual median relative differences in percent (%) per hectare of crop-specific cropland area and grid cell of the year 2010 for: (a) Wheat, (b) rice, (c) maize, and (d) soybean for the 50 year simulation period.

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