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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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S1 Supplementary information to methods and data

S1.1 Crop functional types represented in LPJmL5.0-tillage-cc

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

S1.2 Model input data

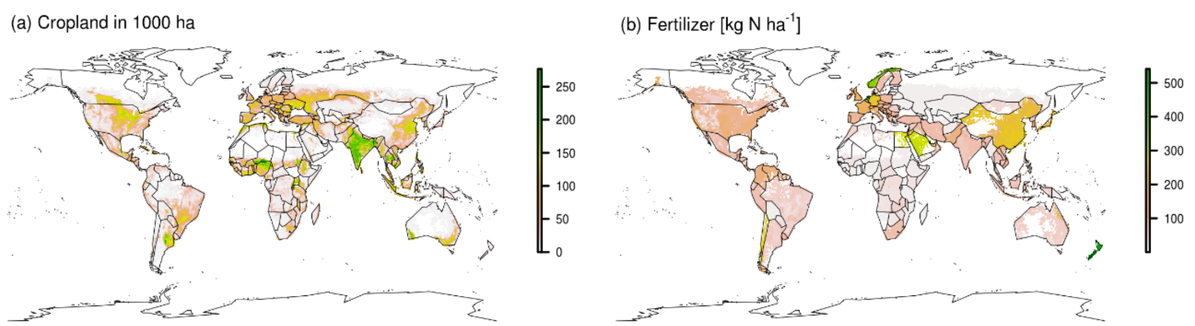

Figure S1.2 Maps depict the spatial pattern of: (a) Physical cropland in 1000 hectares per grid cell, and (b) Mineral N fertilizer application rate in kg N ha^{-1}, both based on LUH2v2 (Hurtt et al., 2020) for the year 2010, which were used as model input data for the simulations and for post-processing model output data (white as no cropland).

S1.3 Overview simulation setup for management scenarios

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

Simulation step	Abbrevi-ation	Tillage setting	Soil cover cropland during main crop off-season periods	Land use[a] and other management settings	Number of years	Climate[b] input data
1. Spin-up:						
1.1. Potential natural vegetation	-	-	-	no land use	7000	repeated (1901-1930)
1.2. Land use	-	tillage	bare soil fallow	static at level of 2010	390	repeated (1901-1930)
2. Land management scenarios:						
2. 1. Baseline	REF	tillage	bare soil fallow	static at level of 2010	50	dynamic (1962-2011)
2.2. Cover crops	CC	tillage	cover crops	static at level of 2010	50	dynamic (1962-2011)
2.3. Cover crops with no-tillage	CCNT	no-tillage	cover crops	static at level of 2010	50	dynamic (1962-2011)
2.4. No-tillage	NT	no-tillage	bare soil fallow	static at level of 2010	50	dynamic (1962-2011)

[a] Hurtt et al. (2020)

[b] Becker et al. (2013); Tans and Keeling (2015)

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

We applied a time series of the global annual CA cropland per grid cell covering the years 1974-2010 (Fig. S1.4). This dataset was obtained combining data of historical physical cropland (LUH2v2 by Hurtt et al. (2020) (years 1974-2010) (Sect. 2.4, 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 of national reported CA cropland 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 and the physical cropland data. 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 CA area data were downscaled to the grid scale at 0.5 degree resolution, according to the likelihood of CA adoption on cropland using methods described in Porwollik et al. (2019).

Historical annual shares of reported and mapped Conservation Agriculture area on global cropland rose from 0.2 % in the year 1974 to about 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, including tillage practices and sensitivity to main crop residue removal rates.

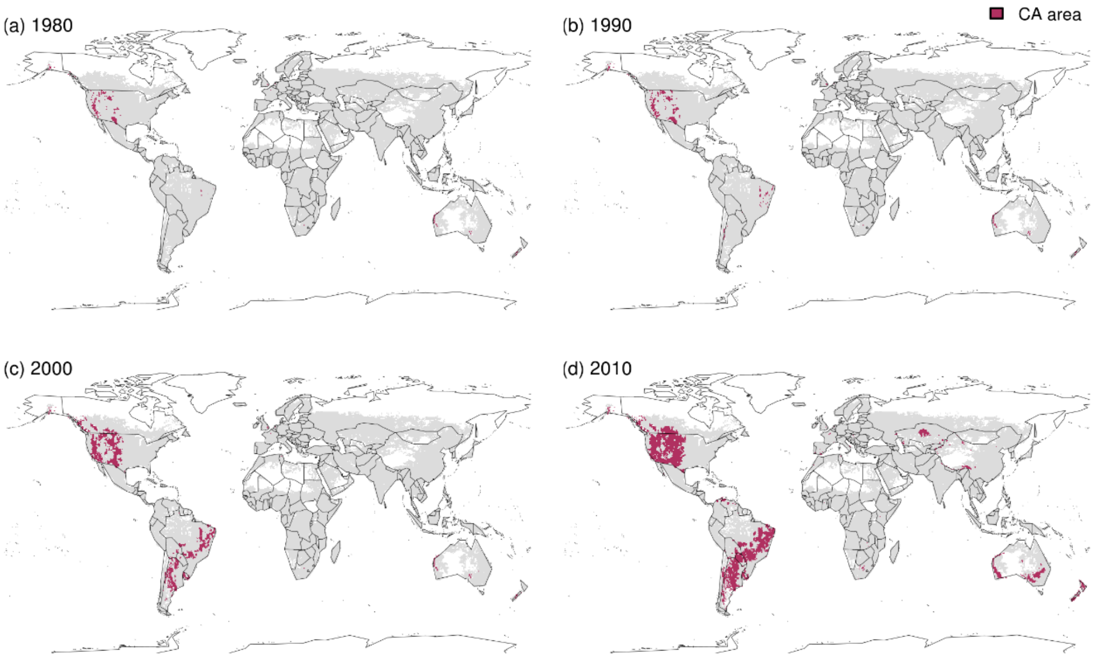

Figure S1.4 Maps (a-d) of global gridded physical cropland mapped with Conservation Agriculture (purple) and conventional tillage practices (grey) per grid cell, here showing time slices of the annual gridded time series data applied in this study for the years: 1980, 1990, 2000, and 2010, respectively,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

S2 Supplementary information to simulated cropland management scenario results

S2.1 Spatial pattern of changes in soil C and N leaching rate due to cover crop management

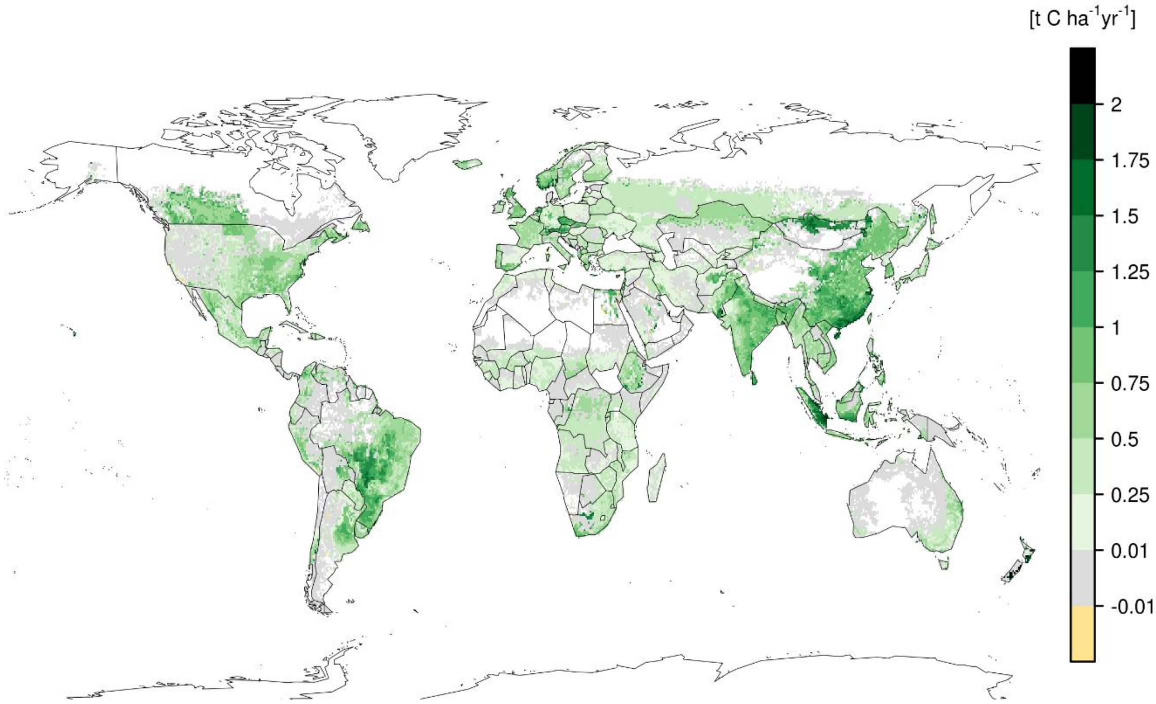

Figure S2.1.1 Map of average annual soil carbon sequestration rates in t C ha^{-1} yr^{-1} per grid cell obtained with cover crops (CC), as absolute difference to the soil carbon stock in the control scenario with bare fallow (REF) divided by the management duration (Eq. 1), per cropland hectare and grid cell in the 50th year of the simulation period (white as no cropland).

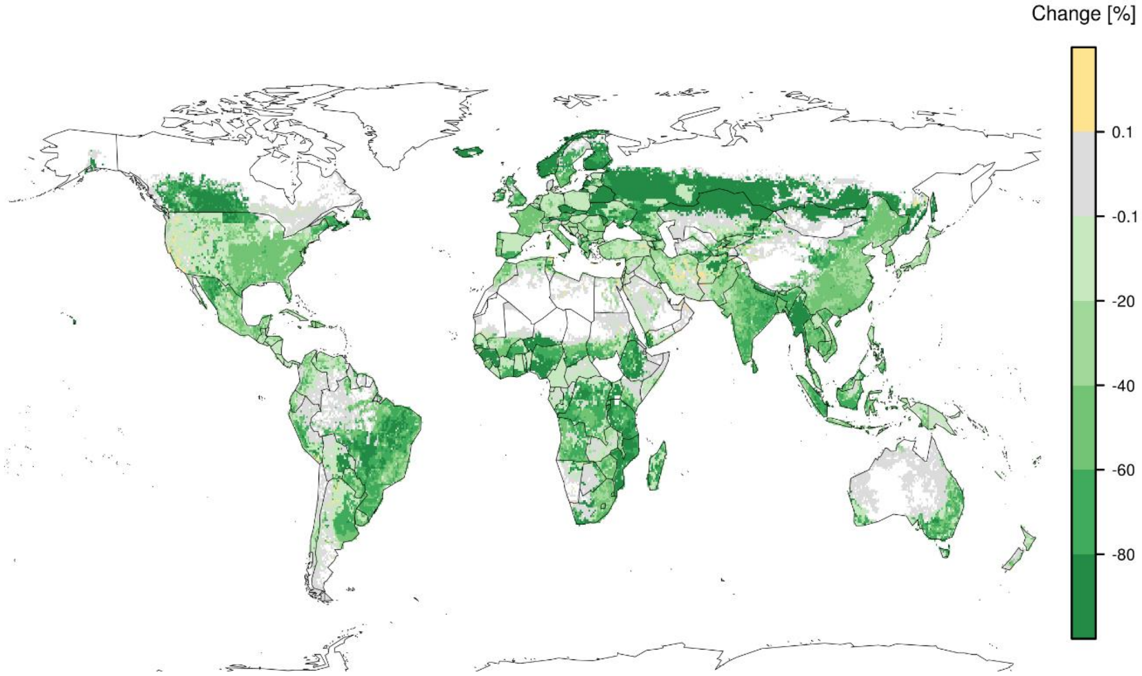

Figure S2.1.2 Map displays the changes of soil N leaching rates from cropland as annual median relative difference in percent (%) per hectare and grid cell due to cover crops (CC) relative to the control scenario with bare fallow (REF) for the 50 year simulation period.

S2.2 Simulated responses to CCNT and NT on global cropland aggregated per decade

Table S2.2 (As Table 1 in Sect. 4.1) Changes of assessed agroecosystem variables due to simulated cover crops with no-tillage (CCNT), and no-tillage (NT), both compared to the baseline management scenario with conventional tillage and bare soil fallowing practices (REF), as area-weighted and aggregated median (and quartiles (Q1, Q3)) across global cropland or crop-specific area for the first and last decades of the 50 year simulation period.

Management scenario:		**ΔCCNT**		**ΔNT**	
	Unit per year	**First decade median (quartiles)**	**Last decade median (quartiles)**	**First decade median (quartiles)**	**Last decade median (quartiles)**
Soil C sequestration rate	t C ha^{-1}	0.72 (0.24, 1.29)	0.54 (0.29, 0.83)	0.08 (0.04, 0.20)	0.01 (0, 0.05)
N leaching rate	%	-57.9 (-80.6, -21.1)	-72.6 (-87.9, -52.2)	-13.8 (-38.1, 4.5)	-20.8 (-46.0, -0.8)
Wheat yield	%	0.0 (-2.7, 2.3)	-0.4 (-4.9, 1.8)	0.8 (-0.01, 3.87)	0.8 (-0.2, 3.7)
Rice yield	%	-2.2 (-8, 1.8)	-3.6 (-8, 2.3)	1.2 (-0.9, 5.3)	1.2 (-1.3, 5.6)
Maize yield	%	1.1 (-4.7, 17.0)	0.8 (-13.6, 16.8)	4.52 (0, 20.4)	4.9 (-0.1, 21.3)
Soybean yield	%	9.3 (1.1, 30.5)	9.3 (1.6, 28.6)	9.3 (1.1, 30.6)	9.6 (1.5, 30.1)
Average change in yield	%	2	1.5	3.9	4.1

S2.3 Soil N immobilization rate and gross N mineralization rate with management duration

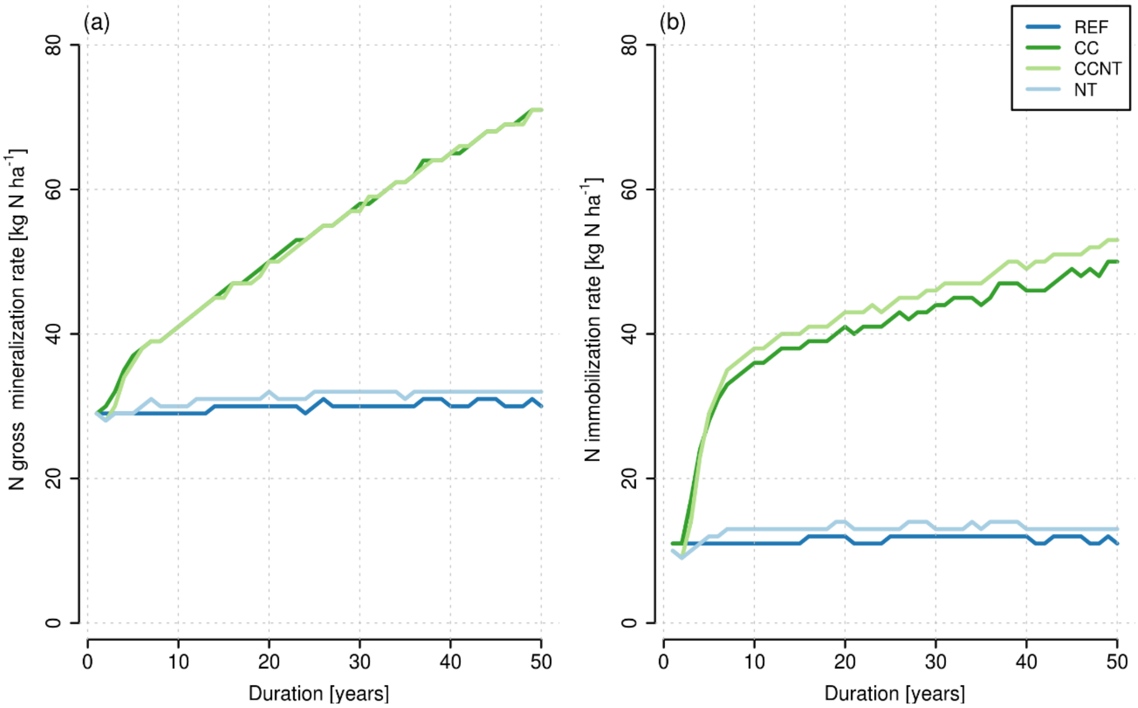

Figure S2.3 Annual global aggregated area-weighted median: (a) Gross N mineralization rates, and (b) N immobilization rates for global cropland soils during the 50 year period as lines for each simulated management scenario (REF, CC, CCNT, and NT).

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

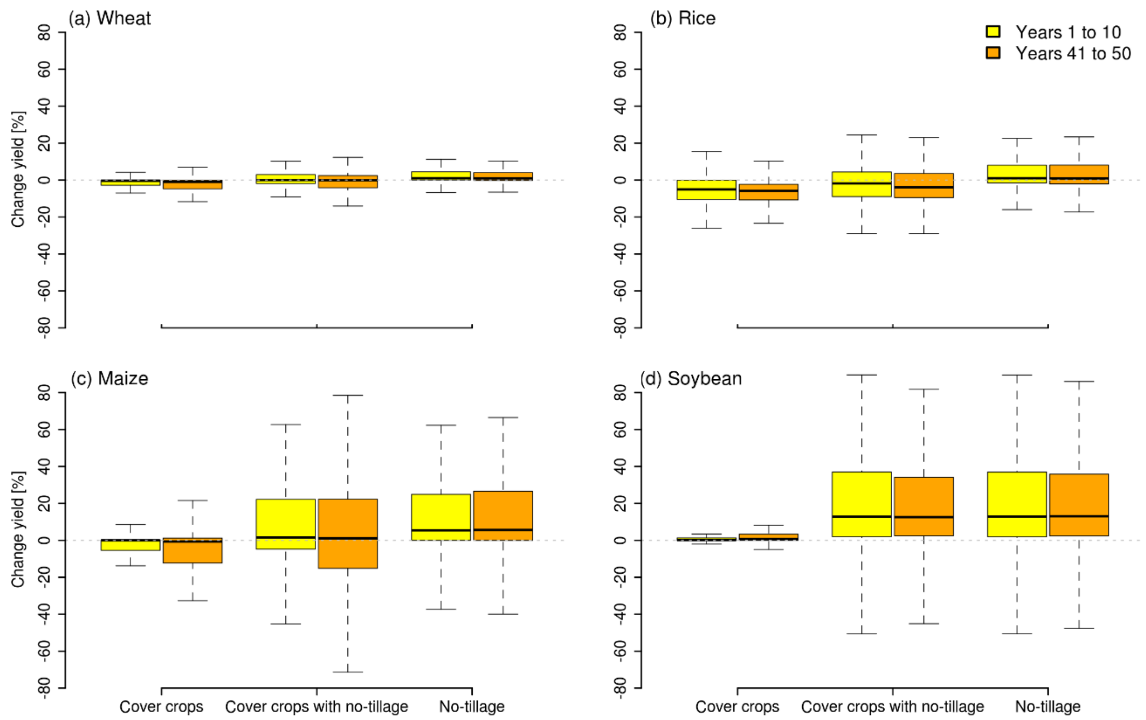

Figure S2.4.1 Panels (a-d) displaying changes in rainfed wheat, rice, maize, and soybean yields as boxplots of relative differences in percent (%) area-weighted by crop-specific physical cropland, due to alternative management practices (CC, CCNT, and NT) compared to the baseline (REF) for the first (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). The boxplots show the distribution of responses per hectare across crop-specific rainfed physical cropland used here for the year 2010, as 322 million ha for wheat, 278 million ha for maize, 85 million ha for rice, and 82 million ha for soybean.

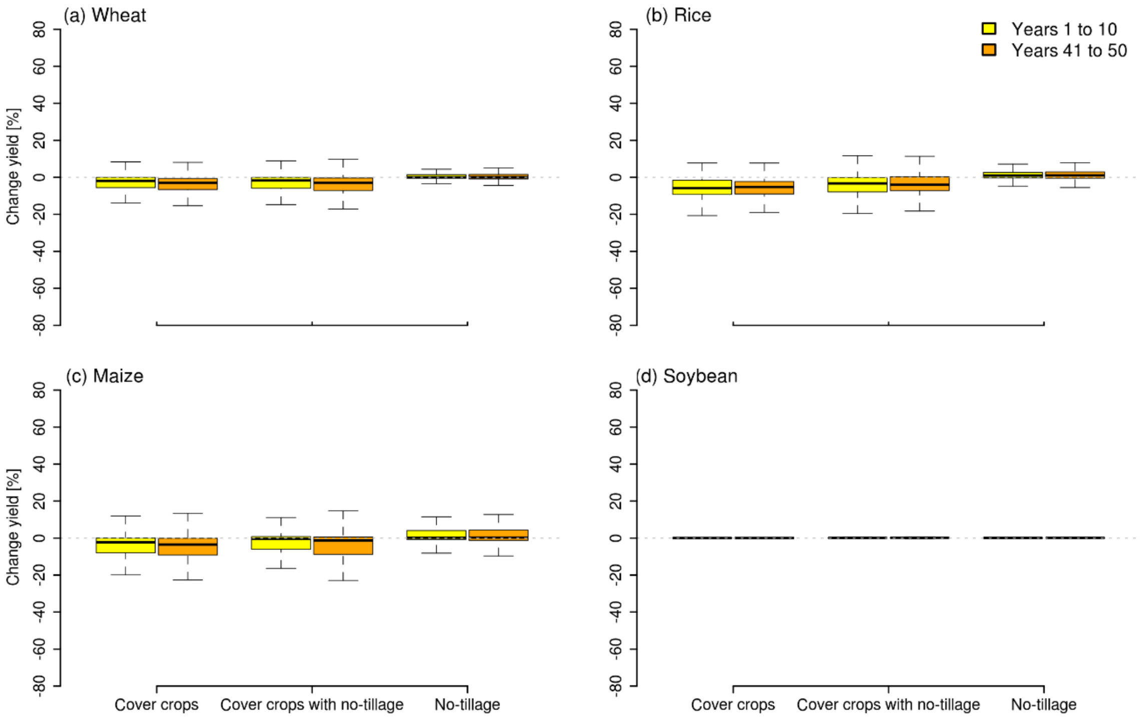

Figure S2.4.2 Panels (a-d) displaying changes in irrigated wheat, rice, maize, and soybean yields as boxplots of relative differences in percent (%) area-weighted by crop-specific physical cropland, due to alternative management practices (CC, CCNT, and NT) compared to the baseline (REF) for the first (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). The boxplots show the distribution across crop-specific rainfed physical cropland used here for the year 2010, as 47 million ha for wheat, 54 million ha for maize, 46 million ha for rice, and 10 million ha for soybean.

S2.5 Land management impacts on mapped CA area

Table S2.5 Calculated changes per management scenario (CC, CCNT, and NT), when estimates were remapped to the spatial and temporal evolving gridded pattern of the annual dynamic CA area during the years 1974-2010, area-weighted, and aggregated median (and quartiles (Q1, Q3)) per variable across total CA cropland (for soil C and N leaching rate) or crop-specific area (for average rainfed and irrigated yields) with CA.

	Unit per year	Cover crops median (quartiles)	Cover crop and no-tillage	No-tillage median (quartiles)

			median (quartiles)	
Soil C sequestration rate	t C ha^{-1}	0.47 (0.01, 1.12)	0.85 (0.32, 1.42)	0.27 (0.15, 0.4)
N leaching rate	%	-38.1 (-68.4, -0.7)	-56.9 (-80.4, -13.4)	-18.4 (-46.8, 10.5)
Wheat yield	%	0 (-1.2, 0)	6.4 (0.2, 29.4)	7.4 (0.5, 30.6)
Rice yield	%	-5.3 (-10.8, 0)	5.6 (-3.1, 34.8)	10.9 (1.9, 42.9)
Maize yield	%	0.01 (-3.7, 1.1)	23.7 (3.3, 84.1)	31 (9, 94.6)
Soybean yield	%	0.2 (0, 2)	27.8 (3.1, 78.9)	28.9 (3.3, 81.1)
Average change in yield	%	-1.3	15.9	19.6

S2.6 Simulated responses to cover crop and tillage practices in comparison to values found in the literature

Table S2.6 Responses to cover crops (CC) in comparison to the control scenario 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. 2.5 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 aggregated area-weighted median (and quartiles (Q1, Q3)) responses of agroecosystem variables 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 reported 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}

Time period (years)	Simulated ΔCC median (quartiles)	Literature estimate	Unit per hectare per year	Literature type	Literature source
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 simulations of 'improved arable land management practices' for 0-25 cm depth, total global potential of 32-64 Pg soil C accumulation on agricultural land after 87 years with cover crops, 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 C 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

Time period (years)	Simulated ΔCC median (quartiles)	Literature estimate	Unit per hectare per year	Literature type	Literature source
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 US studies meta-analysis for non-leguminous CC effects 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), value 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 US, range of annual

Time period (years)	Simulated ΔCC median (quartiles)	Literature estimate	Unit per hectare per year	Literature type	Literature source
					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 in US, range of annual changes for soybean yield with CC compared to without
Average change of yields across median changes of averaged rainfed and irrigated yields of the four assessed following main crop types					
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 for experiments of different main crop types and vegetables
1 - 17	-2	not significantly different	%	Meta-analysis	Thapa et al. (2018), non-legumes CC effects 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

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