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# Estimating the Global Influence of Cover Crops on Ecosystem Service Indicators in Croplands With the LPJ-GUESS Model

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**Key Points:**

- Cover crops (CCs) can increase soil carbon sequestration by 0.11–0.15 Pg C per year while reducing N leaching by 34%–41% in global croplands compared with fallow management
- The influence of CCs on cash crop yields varies widely among crop rotations, climates, management duration, and N fertilizer applications
- Legume CCs in no-tillage system is overall identified as a promising practice to achieve environmental sustainability without compromising crop production in agricultural ecosystems

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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**Abstract** Cover crops (CCs) can improve soil nutrient retention and crop production while providing climate change mitigation co-benefits. However, quantifying these ecosystem services across global agricultural lands remains inadequate. Here, we assess how the use of herbaceous CCs with and without biological nitrogen (N) fixation affects agricultural soil carbon stocks, N leaching, and crop yields, using the dynamic global vegetation model LPJ-GUESS. The model performance is evaluated with observations from worldwide field trials and modeled output further compared against previously published large-scale estimates. LPJ-GUESS broadly captures the enhanced soil carbon, reduced N leaching, and yield changes that are observed in the field. Globally, we found that combining N-fixing CCs with no-tillage technique could potentially increase soil carbon levels by 7% (+0.32 Pg C $yr^{-1}$ in global croplands) while reducing N leaching loss by 41% (−7.3 Tg N $yr^{-1}$) compared with fallow controls after 36 years of simulation since 2015. This integrated practice is accompanied by a 2% of increase in total crop production (+37 million tonnes $yr^{-1}$ including wheat, maize, rice, and soybean) in the last decade of the simulation. The identified effects of CCs on crop productivity vary widely among main crop types and N fertilizer applications, with small yield changes found in soybean systems and highly fertilized agricultural soils. Our results demonstrate the possibility of conservation agriculture when targeting long-term environmental sustainability without compromising crop production in global croplands.

**Plain Language Summary** Increasing crop productivity while maintaining a healthy environment is a major challenge for global agriculture. Cover crops (CCs), mostly grown during the fallow period and plowed into in soils, are expected to improve soil fertility and crop yields while reducing chemical fertilizer use, but their overall impacts on global croplands remain unknown. This study investigates the long-term influence of cover cropping on three ecosystem service indicators across four dominant farming systems (wheat, maize, rice, and soybean) using an ecological model. We find that adoption of CCs can enhance soil carbon stocks, which would contribute to slowing climate change, and benefit environments through reducing nitrogen pollution to water bodies. Among the modeled cover crop species, legumes show higher potential in increasing cash crop yields than non-legumes, but the effect is highly dependent on the crop rotation, chemical fertilizer rate, and management duration. Our results highlight that proper implementation of legume CCs can support food security and environmental sustainability in global agricultural ecosystems.

## 1. Introduction

Over recent decades, both global cropland areas and synthetic nitrogen (N) fertilizer application have greatly increased to feed the growing population (FAOSTAT, 2023) but with large detrimental side-effects on the environment. Estimates suggest that the conversion of natural vegetation (e.g., forests and grasslands) to cropland has reduced soil organic carbon (SOC) stocks by 32%–36% in temperate (Poeplau et al., 2011) and 25%–30% in tropical regions (Don et al., 2011). Management intensification has also caused soil fertility decline (Lal, 2004), air pollution (Reay et al., 2012; Tian et al., 2020), and freshwater eutrophication (Moss, 2008). Gaseous N emissions from fertilizer application have increased by 46% (to 3.8 Tg N $yr^{-1}$) for nitrous oxide ($N_2O$) (Tian et al., 2020) and by 78% (to 58 Tg N $yr^{-1}$) for ammonia ($NH_3$) (L. Liu et al., 2022) over the past four decades. The SOC loss from the expansion and management of agricultural land, combined with the N loss from the intense use of

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fertilizer greatly contribute to greenhouse gas (GHG) emissions and accelerate global warming, while undermining sustainable food production (Lu & Tian, 2017). It is crucial to enhance cropland SOC sequestration and to reduce N losses in order to mitigate climate change while still maintaining and/or increasing agricultural production for food security (Arneth et al., 2021; Poeplau & Don, 2015; P. Smith et al., 2020).

The imbalance between carbon (C) inputs (e.g., plant residue and manure application) and outputs (e.g., through crop harvest, decomposition of residues, leaching, and soil erosion) drives SOC storage changes in croplands. The adoption of minimum soil disturbance (e.g., no- or reduced tillage) has for many years been recommended as an important strategy in conservation agriculture (CA) systems to slow down the decomposition of soil organic matter (SOM) pools (Lal, 2004). However, it has been reported that the SOC benefits of no-till farming are statistically significant only in the topsoil (0–15 cm) and decline with soil depth (Haddaway et al., 2017). In global meta-analyses (Luo et al., 2010; Powlson et al., 2014), SOC stocks under no-till cropping systems were sometimes found to be even lower than conventional tillage in the deeper soil layers (>30 cm). Increasing C inputs to the soils are thus expected to be an alternative management practice for achieving SOC enhancement (Poeplau & Don, 2015). Cover crops (CCs) are plants that mostly grow during the fallow period and are incorporated into the soils as "green manure" before sowing the subsequent main crop. Experimental evidence has indicated that planting CCs within agricultural rotations may significantly increase SOC stocks by 13.8%–17.3% over a period of up to 54 years, compared to management in which the off-season is left fallow, with a global mean sequestration rate of 0.32–0.56 Mg $ha^{-1}$ $yr^{-1}$ (Jian et al., 2020; Poeplau & Don, 2015). In addition to increasing organic matter inputs, CCs also are able to take up excess N from the soil and thus reduce N leaching (Nouri et al., 2022; Thapa et al., 2018; Tonitto et al., 2006), as well as to prevent the soils from the compaction and erosion that happen when soils are bare (Kaye & Quemada, 2017). Moreover, using legume CCs in particular as "green manure" has been discussed as a promising technique to maintain and/or improve soil fertility and crop production because of their capacity to fix N from the atmosphere, with the co-benefits of reducing chemical fertilizer use (Abdalla et al., 2019; Ciampitti & Salvagiotti, 2018). However, these CC effects vary widely regionally due to soil properties, climate at a location, crop management, and cover crop types (Abdalla et al., 2019; Jian et al., 2020; Marcillo & Miguez, 2017; Quemada et al., 2013).

Process-based ecological models have the potential to quantify the impacts of agricultural practices on ecosystem carbon-nitrogen (C-N) and water cycles over large geographic regions and long time periods due to their mathematical representation of vegetation and soil interactions under varying environmental conditions and management (McDermid et al., 2017; Pongratz et al., 2018). These models have been widely used to investigate soil C-N dynamics and crop yields in response to CCs in different farming systems (e.g., APSIM, Chatterjee et al., 2020; DSSAT, Salmerón et al., 2014; DNDC, Singh & Kumar, 2022; ECOSYS, Qin et al., 2023). However, compared to site-level modeling studies, an assessment of the impacts of CCs across regions or globally is still lacking, as a result of inadequate management information (e.g., spatial pattern of cover crop types) and missing or incomplete cover cropping representation in models (Porwollik et al., 2022). For large-scale C-N cycle modeling assessments, alternative agricultural practices so far have been evaluated through stylized model setups with homogenous assumptions of management intensities (Jang et al., 2021; Lutz et al., 2020; Ma, Rabin, et al., 2022; Olin, Lindeskog, et al., 2015). For example, Olin, Lindeskog, et al. (2015) used the LPJ-GUESS dynamic vegetation model to explore the impacts of CCs on SOC sequestration rate across global agricultural ecosystems, assuming that all cropland grid cells adopted the same herbaceous cover crop without symbiotic N fixation. Similarly, to realistically reflect the spatial pattern of cover cropping, a recent modeling study performed by Porwollik et al. (2022) estimated with the LPJmL dynamic vegetation model how CA globally might affect soil C-N and yields in response to non-legume CCs across four cropping systems. Their model results showed the potential of cover cropping for climate change mitigation via enhanced soil C pools, but the authors suggested that future modeling assessment for N-fixing CC cultivation would be needed since this practice is identified as one practical strategy to address the conflict between the growing needs for crop production and the associated environmental problems of N loss (Abdalla et al., 2019). To date, no study has applied process-based models globally to investigate how no-till farming and legume CCs jointly affect agricultural ecosystem services, particularly in terms of soil C sequestration, N leaching from cropland, and crop yields.

Here, we employ the process-based vegetation model LPJ-GUESS (Ma, Olin, et al., 2022; Olin, Schurgers, et al., 2015; B. Smith et al., 2014) to explore the potential contribution of herbaceous N fixers to the sustainable development of agriculture production. The objective of this study is to assess and compare the effects of two cover crop types—leguminous and non-leguminous grasses—and tillage practices on SOC stocks, N leaching loss, and agricultural productivity across global cropping systems. These three modeled ecosystem service indicators are extensively examined with worldwide site-level observed data and compared against global-level estimates from the existing literature. We aim to quantify the temporal and spatial pattern of CC impacts and to discuss the potential of this practice for climate change mitigation and crop production enhancement under present-day climate conditions.

## 2. Materials and Data

### 2.1. Model Description

LPJ-GUESS is a process-based global vegetation model that can be used to investigate plant and soil C-N dynamics and their interactions in response to changes in environment (e.g., climate, atmospheric $CO_2$ levels, and N deposition) and management (e.g., crop type, N fertilizer, and harvest) through simulating individual- and patch-level plant physiological and biogeochemical processes on a daily time step (B. Smith et al., 2014). Natural vegetation implemented in the model is characterized by 12 plant functional types (PFTs), with 10 woody and two herbaceous types included. PFTs differ in their phenology, photosynthetic pathway ($C_3$ or $C_4$), growth strategy, and bioclimatic limitations. Pastures are described as the competition between $C_3$ and $C_4$ grass PFTs, with half of aboveground biomass harvested annually to represent grazing impacts (Lindeskog et al., 2013). Four crop functional types (CFTs)—two temperate $C_3$ crops with spring and autumn sowing dates, a tropical $C_3$ crop representing rice, and a $C_4$ crop representing maize—are simulated to represent croplands, with crop-specific differences in morphological traits, dynamic C-N allocation patterns, heat requirements for growth, and N fertilization management (Olin, Schurgers, et al., 2015). Two new CFTs (i.e., soybean and pulses) with biological N fixation (BNF) have recently been added to account for the effects of legume-based cropping systems on global terrestrial N cycle (Ma, Olin, et al., 2022). For large-scale applications, the sowing date in each grid cell depends on a set of rules driven by crop- and climate-specific characteristics, with five seasonality types represented (see Waha et al. (2012) for details). Crops are harvested annually when the dynamic potential heat units (i.e., accumulated degree-days above a base temperature for each CFT) are fulfilled (Olin, Schurgers, et al., 2015). To account for crop post-harvest losses caused by mechanical damage or poor handling conditions, a harvest efficiency of 90% is used to adjust the modeled crop yields (Lindeskog et al., 2013). At present, within-year multi-cropping systems, which are common in tropical regions, have not been implemented in the model.

Cropland management options represented in LPJ-GUESS include irrigation, tillage, crop residue retention, N fertilizer and manure application, and cover crop grasses grown between two cropping seasons. Irrigation water is estimated as the amount of plant water deficit in the model and is added to the soil automatically when crops suffer from water stress. The effect of conventional tillage on heterotrophic respiration is simulated as a tillage factor of 1.94, which modifies the decay rate of four SOM carbon pools throughout the year and accelerates the soil decomposition on agricultural lands (Chatskikh et al., 2009; Pugh et al., 2015). In the standard LPJ-GUESS setup, 75% of aboveground crop residue is removed from the fields after harvest; the rest, combined with root biomass, is assumed to enter to the soil litter pool for decomposition. Synthetic N fertilizer is added to the soil mineral N pool for plant uptake at three crop development stages, with varying application rates for each CFT (see Table A2 in Olin, Lindeskog, et al., 2015). Manure is applied as a single input to cropland at sowing to account for the time required for manure N to be made available for crops. Manure is assumed to have a C:N value of 30 and is added to metabolic and structural SOM pools for decomposition (Olin, Lindeskog, et al., 2015). A variety of cover cropping options are used in this study and are described in detail below (see Section 2.2).

C-N dynamics of the soils in LPJ-GUESS are modeled by 11 SOM pools differing in C:N ratios and resistance to decay, following the CENTURY model (Parton et al., 1993). Decomposition of SOM pools results in release of $CO_2$ to the atmosphere (respiration) and C and N transfers between soil pools (B. Smith et al., 2014). C input to the receiver pool drives N mineralization or immobilization, as a result of maintaining mass balance and prescribed C:N ratios of the donor and receiver pool. Net N mineralization (i.e., mineralization minus immobilization), together with industrial N fertilizer and atmospheric N deposition, determine the size of the total soil mineral N pool, which is depleted by plant N uptake, as well as by crop ecosystem N losses through N leaching and gaseous N emission on a daily time step (Wårlind et al., 2014; Zaehle & Friend, 2010). Following Parton et al. (1993), mineral N leaching in the model is proportional to soil nitrate concentration and constrained by percolation rate and soil water content. N losses through soluble organic leaching are also added in LPJ-GUESS and determined by N decreases in soil microbial SOM nitrogen pool (due to decomposition), water percolation, and soil sand fraction (Wårlind et al., 2014).

**Table 1**
*Global Simulation Setups Representing Different Cover Crop Managements (See Section 2.3.2)*

| Simulation | NoCC | $CC_L$ | $CC_{NL}$ | $CC_L$NT |
|---|---|---|---|---|
| Legume cover crop | No | N-fixing $C_3$ grass | No | N-fixing $C_3$ grass |
| Non-legume cover crop | No | No | Competing $C_3$ and $C_4$ grasses | No |
| Main-crop residue retention | 25% | 25% | 25% | 25% |
| Manure application | Yes | Yes | Yes | Yes |
| Mineral N fertilizer | Yes | Yes | Yes | Yes |
| Tillage | Yes | Yes | Yes | No |

*Note*. NoCC—control treatment with bare fallows; $CC_L$—legume cover crops; $CC_{NL}$—non-legume cover crops; $CC_L$NT—combined management practice with legume cover crops and no tillage.

## 2.2. Representation of Cover Crops

CCs implemented in LPJ-GUESS so far have been simulated as competing temperate $C_3$ and tropical $C_4$ grasses grown annually between two consecutive growing seasons of main crops, replacing bare-soil fallow periods. Cover crop grass is sown on the fifteenth day after the harvest of the main crop, starting with a seedling that has an initial C mass of 0.01 kg C $m^{-2}$ and C:N ratio 16 (Olin, Lindeskog, et al., 2015). Daily C and N mass in grasses are allocated to root and leaf pools based on a prescribed root:shoot partitioning ratio of 2 (Sainju et al., 2017), which is dynamically adjusted depending on plant water status. In the case of water stress, root allocation is increased (i.e., root:shoot partitioning ratio > 2) to help plants overcome the water limitation, following Penning de Vries et al. (1989). Cover crop grasses on fallow cropland in the simulations do not receive any management inputs (i.e., they grow under rain-fed and unfertilized conditions). Fifteen days before planting the next main crop their shoot and root biomass are added to the surface litter and the soil metabolic/structural SOM pools, respectively, for further decomposition. At this point, interplanting CCs with main crops (i.e., two plants growing beside each other at the same time) is not implemented in the model.

To account for legume CC impacts on agricultural ecosystems, we developed a new herbaceous PFT in LPJ-GUESS based on the existing $C_3$ grass type (Olin, Lindeskog, et al., 2015) but with BNF processes added. As in our previous work (Ma, Olin, et al., 2022), the amount of N fixed by the BNF $C_3$ grass is a function of soil temperature, soil water and N availability, plant development stage, and a potential N fixation rate that is dependent on net primary productivity (NPP; see Text S1 in Supporting Information S1). The fixed N is partially transported to leaves and subsequently supports photosynthesis, resulting in additional C benefits through reducing N limitation on leaf carboxylation capacity. Since fixing N from the atmosphere requires substantial chemical energy (Ryle et al., 1979), we assume that up to 50% of daily NPP may be consumed for N fixation in the model, following the findings from previous studies (Kaschuk et al., 2009, 2010; Ma, Olin, et al., 2022). More details are provided in Supporting Information S1 and in B. Smith et al. (2014).

## 2.3. Experimental Setups

Our study is divided into two parts. First, we test the model's ability to reproduce the observed responses in SOC stocks, N leaching, and crop yield to N-fixing and non-N-fixing CCs at various field trial sites around the world. Next, we perform four global simulations of cover crop cultivation and tillage systems (Table 1). Our analyses focus on impacts on SOC stocks, N leaching, and crop yield, first evaluating the model results against estimates from global-level studies and statistics, then analyzing and discussing the potential contribution of CCs to environmental sustainability and food security under three CA scenarios (see Section 2.3.2 below).

Model spin-up follows the protocol in Ma, Olin, et al. (2022). In order to build up the stabilized soil C-N levels on cropland, all simulations in this study are initialized with a 500-year spin-up using atmospheric carbon dioxide ($CO_2$) concentration from 1901 and repeating de-trended climate from 1901 to 1930 (see Table S1 in Supporting Information S1 for data sources). During spin-up, potential natural vegetation (PNV) is simulated for the first 470 years, and then the cropland fraction linearly increases from zero to the first historic value (1901) in the last 30 years. Monthly atmospheric N deposition simulated by CCMI (NCAR Chemistry-Climate Model Initiative) from 1901 to 2014 is used and interpolated to the same resolution of the climate forcing (0.5° × 0.5°) (Tian et al., 2018). Model input data are summarized in Table S1 in Supporting Information S1, with the specific simulation experiment setups described in detail below.

#### 2.3.1. Model Evaluation at Site Scale

To examine the model performance, cover crop field trials that also report observations of SOC stocks, N leaching, and crop yield were collected from the existing literature using the following criteria: (a) a control treatment with bare fallows (NoCC) had to be present as part of the field-based cropping experiments. We excluded greenhouse-based and vegetable farming studies, which cannot be represented by LPJ-GUESS at present. (b) Due to the absence of intercropping systems in the model (see Section 2.2 above), we only selected field trials in which CCs were either grown during the bare fallow period or undersown in main crops. For the latter case, CCs usually coexist with the main food crops for a short while (ca. 1–3 months before the main crop is harvested); CC growth is dormant during the winter months, but continues in spring, and CC crops are then terminated several days prior to the next planting of the main crop (Valkama et al., 2015). (c) To capture the variability of the observed data, CC treatments needed to cover at least two growing seasons, with the whole plant used as green manure or mulch returning to the fields. (d) Other managements, such as N fertilizer applied to main crops, had to be the same for both control and CC treatments. Cover crop trials that substituted synthetic fertilizer with green manure were thereby excluded.

A total of 43 studies carried out at 41 different sites were compiled for evaluation. Studies investigated the effects of two cover crop functional types, that is, legumes ($CC_L$) and non-legumes ($CC_{NL}$), on soil C sequestration (12 sites), N leaching (13 sites), and crop yields (29 sites) across four cropping systems (wheat, maize, rice, and soybean) and under various water and N management practices (Figure 1) and climatic zones (Ma et al., 2023). Details for these sites—their geographic coordinates, CC and main crop types, the treatment duration, as well as field management practices—are provided in Tables S2–S4 in Supporting Information S1.

Because weather data for most study locations was not available, a gridded climate data set at 0.5° resolution from GSWP3-W5E5 (Cucchi et al., 2020; Dirmeyer et al., 2006; Lange, 2019) was used as input, choosing the grid cell where the experimental sites are located. Likewise, there was not much information on land use during the years preceding the field trials for most sites. Therefore, to maintain SOM pools in equilibrium after model spin-up, we assumed that all sites were under grassland systems from 1901 to 1905, followed by a cropland period of 1906–1910, with this 5-year alternation between grassland and cropland repeated until the field trials began. Since cropland at most sites had already been present for several years at the beginning of the CC experiment, we simulated 5 years of cropland preceding the site trials at those locations for which no other information was reported. Over the experimental period, model runs were performed according to management information reported in the literature (Tables S2–S4 in Supporting Information S1). At the moment LPJ-GUESS does not simulate the cultivation of two crops simultaneously on the same field, whereas undersown CCs in the field experiments are generally grown together with main crops at least 1–3 months (Valkama et al., 2015). To better represent the total length of the cover crop growing season in the model simulations, we adjusted the sowing date of undersown CCs (referred to as the A1 runs in Table S1 in Supporting Information S1) to 1 day after the main crop harvest (instead of the default 15) and terminated the plants 1 day before the establishment of the next primary crop. For CCs solely grown on fallow cropland (A2, Table S1 in Supporting Information S1), their planting and harvest dates were assumed to be the same as the LPJ-GUESS standard setup (see Section 2.2), following the common field practice at most sites (Duval et al., 2016; Kaspar et al., 2012; Mazzoncini et al., 2011). In addition, site-specific soil physical properties—bulk density and fractions of sand, silt, and clay—derived from the literature (Ma et al., 2023) were used as external forcing to further calculate corresponding soil water characteristics and held constant across all CC simulations.

#### 2.3.2. Global Agricultural Ecosystem Response to Cover Cropping

In this experiment we performed simulations with four CFTs—wheat, maize, rice, and soybean—which jointly provide more than two-third of the world's food supply (FAOSTAT, 2023). To detect how CCs affect cropland ecosystem services, two cover crop types—leguminous ($CC_L$) and non-leguminous ($CC_{NL}$) grasses were assessed. An additional combined practice, with N-fixing cover crop and no tillage ($CC_L$NT), was used to represent important aspects of CA. Model outputs of these three practices were compared to a control simulation with bare fallow (NoCC), applying the simulation setup given in Table 1.

The model experiments started with a baseline simulation of the historical period (1901–2014) under NoCC management after model spin-up, using dynamic gridded climate, land use/land cover, and N fertilizer data

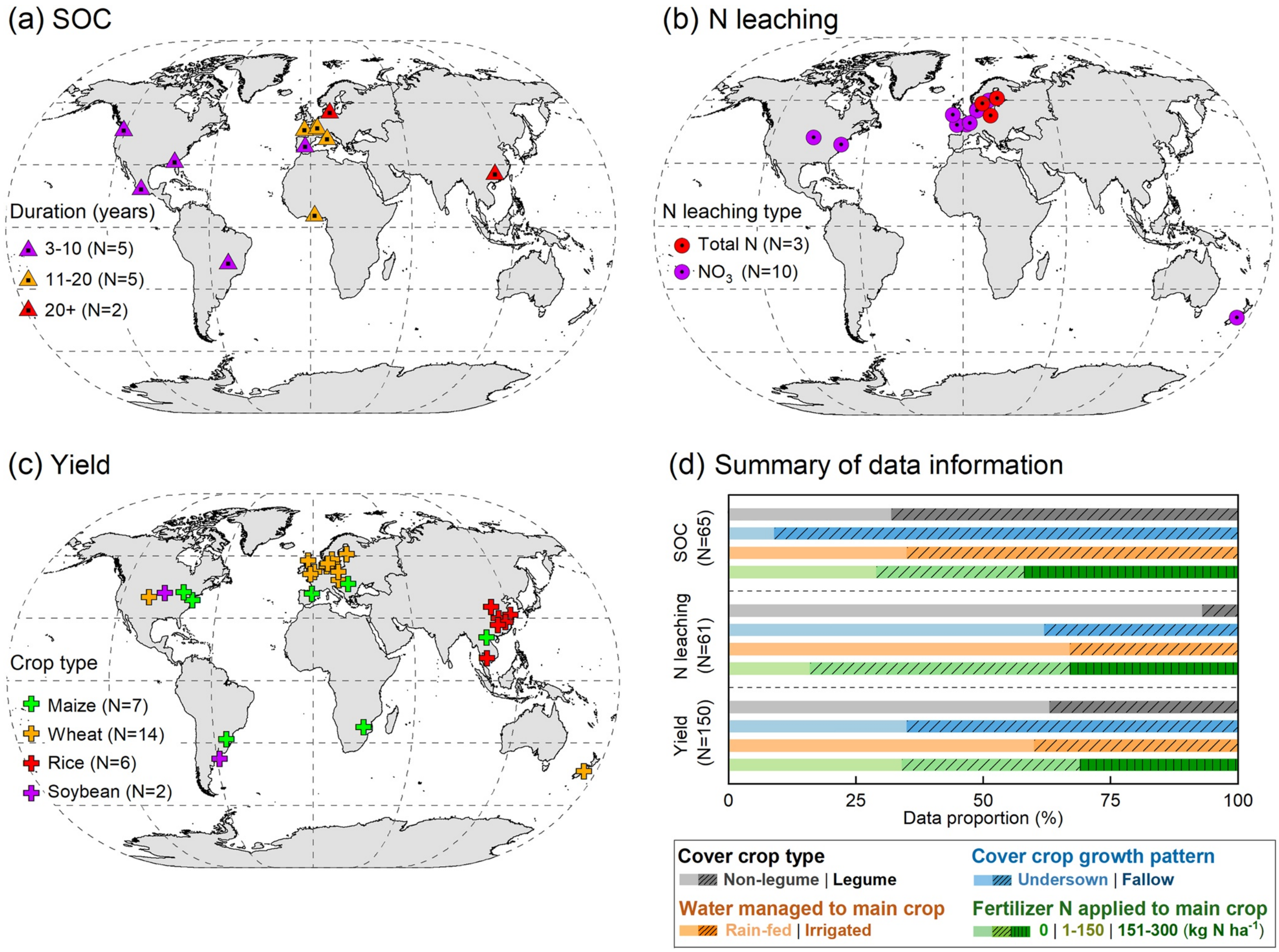


**Figure 1.** Distribution of cover cropping field studies used for model evaluation of cropland soil organic carbon (SOC) stocks (a), N leaching loss (b), and crop yields (c). All studied SOC sites (12) had continuously practiced cover crop (CC) cultivation for more than 3 years, and the leached N loss at the evaluated sites (13) were reported as either total N (mineral plus organic) or nitrate ($NO_3$). The influence of CC practice on crop production was investigated in four cropping systems (maize, wheat, rice, and soybean) at 29 sites from 16 countries. A summary of field experiments—cover crop types (legumes or non-legumes), growth patterns (undersown or fallow), and water and N fertilizer managements to main crops—is shown in (d).

(0.5° × 0.5°), together with atmospheric $CO_2$ concentration (data information described below). The result of this run was to produce present-day SOM pools on off-season fallow cropland across the globe (Table S1 in Supporting Information S1). This baseline simulation is referred to as B1.

Subsequent runs of four management practices listed in Table 1 branched from this present-day state in 2015 and are referred to as the B2 runs. These simulations ran for 36 years (the maximum duration found in cover cropping field trials in our analyzed sites; see Tables S2–S4 in Supporting Information S1) but are not intended to estimate SOC storage, N leaching and crop production through 2050; rather, they are designed to detect the relative changes in these three ecosystem indicators when replacing bare fallows with CCs. For that reason, we use constant repeated 1995–2014 climate with temperature de-trended, combined with 2014 land use, fertilizer, manure, and $CO_2$ concentration (Table S1 in Supporting Information S1). In order to contrast short-with long-term cover crop impacts, model outputs in the first (years 1–10) and last (years 27–36) decades were used for analysis.

For global-scale applications, LPJ-GUESS was driven by monthly mean temperature, precipitation, solar radiation, and number of wet days from the observation-based CRUJRA v2.1 data set, spanning from 1901 to 2014 at 0.5° resolution (Harris et al., 2020; Kobayashi et al., 2015). Annual atmospheric $CO_2$ concentration was from Meinshausen et al. (2020). Historical land use/land cover input data between 1901 and 2014 were adopted from LUH2 (Hurtt et al., 2020) and were remapped from 0.25° to 0.5° with fractions of natural vegetation, pasture, and cropland given for each grid cell. The growth distribution of various crop types, distinguishing shares of rain-fed and irrigated crop-specific fraction per grid cell, was based on the MIRCA data set around the year 2000 (Portmann et al., 2010) and aggregated to the four CFTs simulated in this study. Thus, although the total cropland area at each grid cell varied annually over the simulation period, the relative fraction of each CFT within that cropland area remained static. To parameterize soil hydraulic properties, cropland soil texture classes in the upper soil layer (0–30 cm) from ISIMIP/GGCMI phase 3 (Volkholz & Müller, 2020) were used and held constant over the course of the model experiments. In addition, CFT-specific industrial N fertilizer and manure inputs were derived from Ag-GRID (Elliott et al., 2015) and Zhang et al. (2017), respectively, ranging from 1901 to 2014 at 0.5° resolution (Figure S1 in Supporting Information S1).

Since large-scale statistics on actual cover crop acreage do not exist, the CA area was used to represent the potential cover crop distribution on agricultural soils, following setups in a recent modeling study (Porwollik et al., 2022). We here performed all global simulations under three CA area scenarios: (a) $CA_{his}$, representing the approximate area of CA practice currently adopted in global croplands; (b) $CA_{pot}$, representing the potential agricultural lands that might implement CA systems under present socio-economic and soil biophysical conditions; (c) $CA_{all}$, assuming all cropland that was under CA management. Spatial pattern of $CA_{his}$ and $CA_{pot}$ were taken from a gridded data set developed by Porwollik et al. (2019), in which national FAO-reported CA area around the year 2005 was downscaled to grid cell level and the potential CA-suitable agricultural lands were estimated based on a range of rule-based approaches. To characterize the $CA_{all}$ scenario, LUH2 land use data at the year 2014 were used. The spatial distribution of these three CA scenarios, as well as their total areas, are shown in Figure S2 in Supporting Information S1.

### 2.4. Data Analysis

Model performance at site scale was evaluated by comparing the simulated and observed ecosystem service indicators—SOC stocks, N leaching loss, and crop yield—in response to the implementation of CCs. For SOC stocks comparison, when the observed values in some field experiments were only provided as concentrations (g kg$^{-1}$), we converted these to stocks (Mg ha$^{-1}$) using Equation 1:

$$\mathrm{SOC}_{\mathrm{stock}} = (\mathrm{SOC}_{\mathrm{con}} \times \mathrm{BD} \times \mathrm{D})/10 \tag{1}$$

where $SOC_{stock}$ and $SOC_{con}$ represent SOC stocks (Mg ha$^{-1}$) and concentration (g kg$^{-1}$), respectively. BD is bulk density (g cm$^{-3}$) and D is soil depth (cm).

The sampled soil depth for SOC and N leaching in our compiled data set varied from 15 to 40 cm and 60–150 cm, respectively (Tables S2–S3 in Supporting Information S1). To compare model outputs with observations, we standardized the measured SOC and N leaching from the original depth to the modeled depth of 150 cm, following the depth distribution function developed by Jobbágy and Jackson (2000) and further described by McClelland et al. (2021):

$$Y = 1 - \beta^{D} \tag{2}$$

$$\mathrm{VAR}_{150} = \frac{1 - \beta^{150}}{1 - \beta^{D0}} \times \mathrm{VAR}_{D0} \tag{3}$$

where $Y$ is the cumulative proportion of the SOC or N leaching from the surface to depth $D$ (cm) and $\beta$ is the relative rate of decrease in these two variables with soil depth. The value of $\beta$ is obtained from a meta-analysis study and set to 0.9786 for SOC and 0.9831 for N leaching (Abdalla et al., 2019). VAR denotes SOC or N leaching; $D_0$ is the original soil depth available in the literature; $VAR_{150}$ and $VAR_{D0}$ represent the cumulative SOC stocks or N leaching at 0–150 cm and original soil depth, respectively.

Based on these post-processed site-level observed data, the accuracy of the model in predicting cropland SOC stocks, N leaching, and crop yield was assessed using adjusted $R^2$ (the goodness of fit for the linear regression analysis), mean error (ME), mean absolute error (MAE), and the root mean square error (RMSE). In addition, to quantify the response of cropland soil C storage to CCs in comparison with the control treatment (NoCC), the annual SOC sequestration rate, $\Delta SOC_{rate}$ (Mg C ha$^{-1}$ yr$^{-1}$), was calculated as:

$$\Delta\mathrm{SOC}_{\mathrm{rate}} = \frac{\mathrm{SOC}_{X} - \mathrm{SOC}_{\mathrm{NoCC}}}{\mathrm{YR}} \tag{4}$$

where $SOC_X$ and $SOC_{NoCC}$ are the respective SOC stocks under the cover crop and control treatments, and $x$ denotes any cover crop practices ($CC_L$, $CC_{NL}$, and $CC_LNT$; see Table 1 for management abbreviations), and YR represents the duration (years) of management.

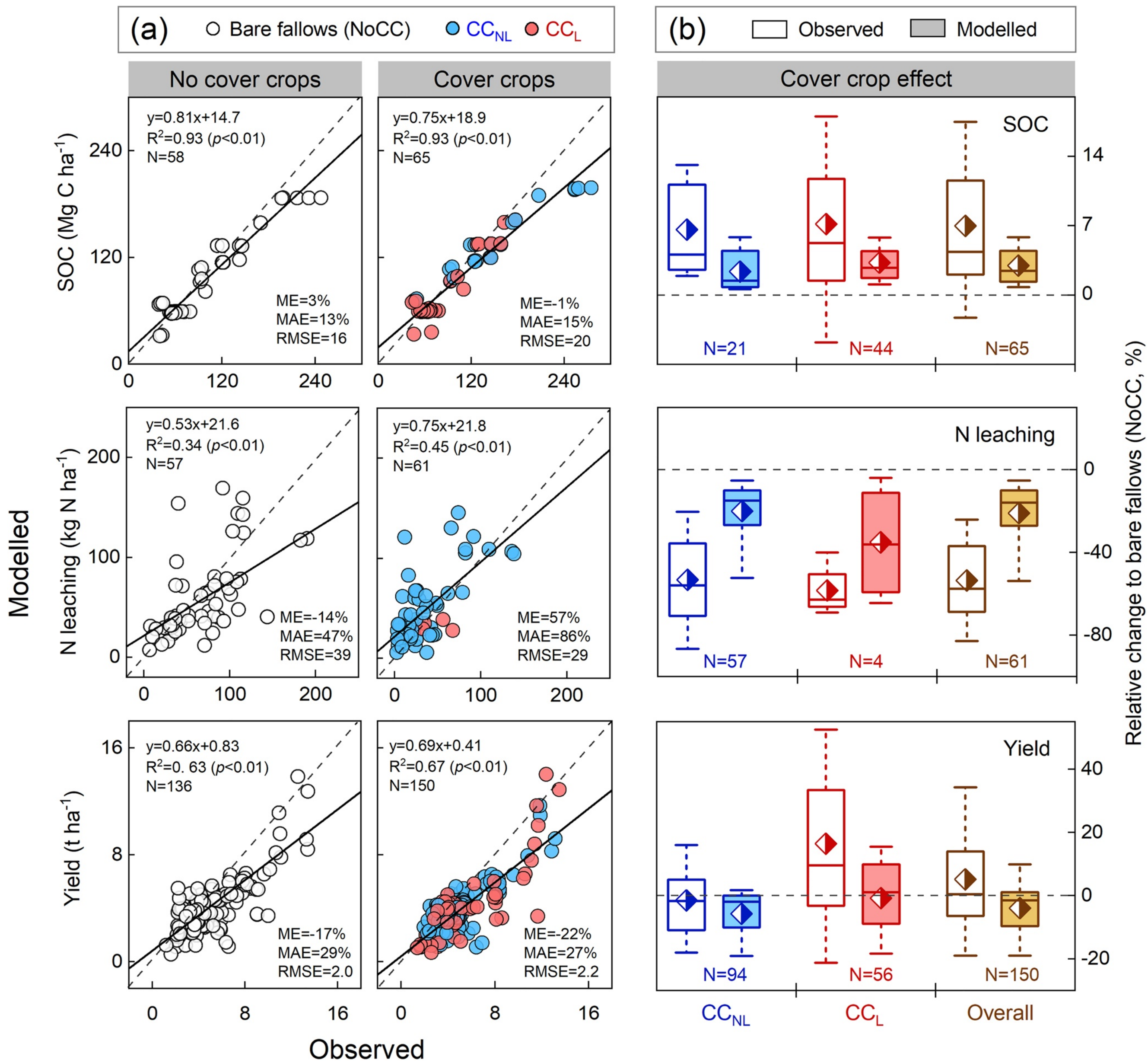


**Figure 2.** Comparison of modeled and observed cropland soil organic carbon (SOC) stocks, N leaching and crop yield (a) and their responses to cover crops (b) across all studied sites. The dashed line in (a) is the 1:1 line and the black bold line is a fitted linear regression; ME and MAE indicate mean error and mean absolute error, respectively (in percent); RMSE is root mean square error, with units Mg C ha$^{-1}$ for SOC, kg N ha$^{-1}$ for N leaching, and t ha$^{-1}$ for yield. Box plots in (b) denote the 5th and 95th percentiles by the whiskers, median and interquartile range are the box lines, and means are symbolized as diamonds. See Section 2.3.1 for treatment abbreviations and their explanations.

## 3. Results

### 3.1. Model Evaluation at Site Scale

#### 3.1.1. Model Performance Across All Sites

Modeled SOC generally agreed well with observations, with high regression slopes (0.75–0.81) and low absolute errors (13%–15%) in the control (i.e., NoCC) and cover crop treatments (Figure 2a). We found enhanced cropland soil carbon stocks in the two simulated cover crop types compared with NoCC, indicated by positive annual SOC sequestration rates of 0.28 and 0.45 Mg C ha$^{-1}$ yr$^{-1}$ (on average) in the CC$_{NL}$ and CC$_L$ simulations, respectively (Table S5 in Supporting Information S1). This compared well with the observed value of 0.48 Mg C ha$^{-1}$ yr$^{-1}$

in the $CC_L$ case, although the model underestimated the soil carbon enhancement (the range between the 5th and 95th percentiles) when all cover crop types were included (the ranges of −2.1% to 17.2% and 0.8%–5.8% for observations and simulations, respectively; Figure 2b).

Simulated N leaching from bare fallow cropland (NoCC) tended to be somewhat lower than the measurements, with a mean underestimation of 14%. By contrast, the model overestimated N losses by 57% in the cover crop experiments (Figure 2a). A positive exponential relationship between N fertilizer rate and N leaching ($p < 0.01$) was observed across a range of field sites in this study (Figure S3 in Supporting Information S1). Simulations from LPJ-GUESS mostly captured this relationship, although higher leached N rates were modeled in the highly fertilized trials (224–260 kg N $ha^{-1}$) compared with measurements (Figure 2a and Figure S3 in Supporting Information S1). Replacing bare fallows with CCs on average reduced N leaching by 54% in the field experiments, with the decreases ranging from 20% to 87% for non-legume types and 40%–68% for legume types (Table S5 in Supporting Information S1). LPJ-GUESS reproduced these mean differences well, but underestimated the relative changes in response to CCs, with the modeled reduction of 5%–53% and 4%–65% in the $CC_{NL}$ and $CC_L$ simulations, respectively (Table S5 in Supporting Information S1, Figure 2b).

In comparison with observations, LPJ-GUESS underestimated crop yields on average by 17%–22% across all field trials (Figure 2a), mainly as a result of simulated lower agricultural productivity in the unfertilized systems, particularly in wheat and rice (Figure S3 in Supporting Information S1). Compared with the bare fallows, using non-legume CCs during the off-season was modeled to reduce the subsequent main-crop production by 2%–16% across four assessed farming systems, larger than the mean observed yield reductions (1%–4%) in the field measurements. However, the implementation of N-fixing CCs in our simulations resulted in yield increases in some cases, with the production changes from −18.0% to 16.0% when all crop types were included, falling within the reported range of −21% to 52% (Table S5 in Supporting Information S1, Figure 2b). In field experiments the yield increase due to legume CCs was largest in unfertilized systems, and the impact of legume cover cropping gradually declined when main crops received high N application rates. The model reasonably reproduced the decreased trend of yield benefits to N fertilizer increases, but generally underestimated these effects in most N fertilization trials (Figure S3 in Supporting Information S1).

### 3.1.2. Soil Organic Carbon Response to Cover Crops

In a long-term (15 years) experiment Mazzoncini et al. (2011) tested the SOC response to agricultural management. Three cover crop treatments (NoCC, $CC_{NL}$, and $CC_L$) with two tillage strategies and four N fertilization rates were conducted in a cropping system that grew first maize, followed by wheat-maize rotation, and sunflower in the last year (Italy, 10.3°E, 43.7°N; see Table S2 in Supporting Information S1). Since the main crop—sunflower—has not been incorporated in the current version of LPJ-GUESS, we modeled this crop type as wheat aiming to test whether we could nevertheless reproduce the general response of SOC to the different managements.

After 15 years of cover cropping, the observed mean SOC stocks in the field trials increased from 92.5 to 89.7 Mg C $ha^{-1}$ in 1993 to 97.7 and 102.3 Mg C $ha^{-1}$ in 2008 for $CC_{NL}$ and $CC_L$ treatment, respectively (Mazzoncini et al., 2011). The modeled soil carbon changes, averaged across a range of management options, were 91.2–97.1 Mg C $ha^{-1}$ in the $CC_{NL}$ simulation and 91.2–98.6 Mg C $ha^{-1}$ in the $CC_L$ simulation over the same period, suggesting overall good model performance although SOC increases in the $CC_L$ simulation were underestimated (Figure 3a). The 15-year adoption of non-legume and legume CCs was simulated to sequester 0.07 and 0.17 Mg C $ha^{-1}$ $yr^{-1}$ of soil carbon ($\Delta SOC_{rate}$, Equation 4), respectively, relative to bare fallows (NoCC). The observations showed similar responses but with higher sequestration rates of 0.26 and 0.57 Mg C $ha^{-1}$ $yr^{-1}$ (Table S6 in Supporting Information S1). Over the experimental period there was an obvious underestimation of the simulated total aboveground biomass for all treatments. This may be partially due to the lower shoot biomass of CCs in the model experiments compared with observations (Figure 3b). Moreover, LPJ-GUESS at this point does not simulate the growth of weeds, which amount to ∼10%–30% of the total aboveground dry matter in the field measurements (Figure 3b).

### 3.1.3. Nitrate Leaching and Crop Yield Response to Cover Crops

The ability of the model to simulate observed nitrate leaching and crop yields in response to CCs was examined using data from a 4-year field experiment carried out in a rain-fed maize-soybean rotation system in Ames, USA (93.7°W, 42.1°N; see Tables S3–S4 in Supporting Information S1). At this site, ryegrass was the overwintering cover crop (Kaspar et al., 2012), solely cultivated on fallow cropland; a legume cover cropping experiment was not conducted in the field.

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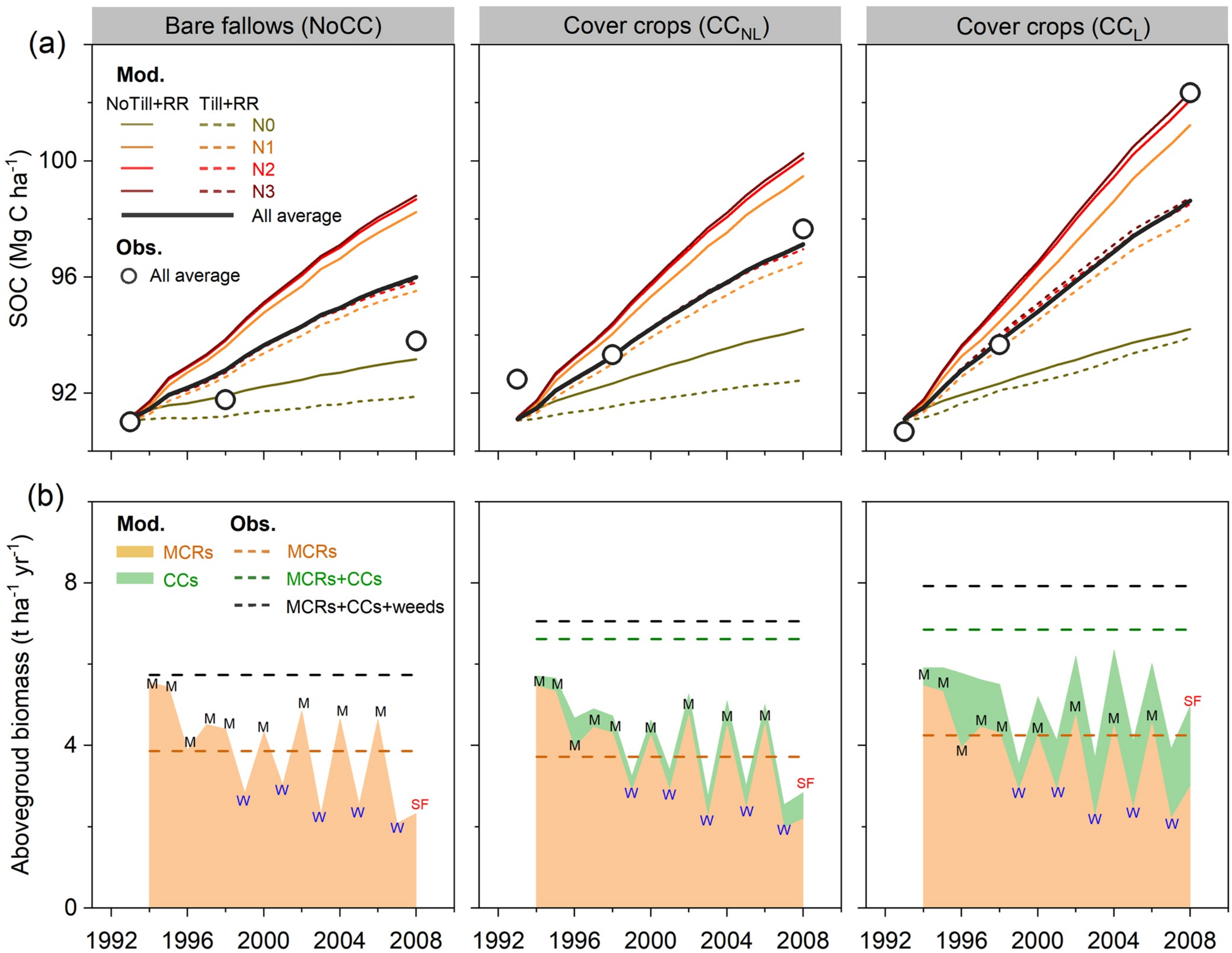


**Figure 3.** Modeled and observed cropland soil organic carbon (SOC) (a) and aboveground biomass (b) under three cover crop treatments at a rain-fed field site with Mediterranean climate in Pisa (Italy) between 1993 and 2008. The main crop of sunflower only planted in the last year of the field experiments was modeled as wheat. The observed SOC stocks in Mazzoncini et al. (2011) were reported as the mean values of two tillage strategies and four N fertilizer levels and were labeled as "All average" in (a). N0, N1, N2, and N3 in (a) are respectively no N, low N, medium N and high N fertilization rates, with 0, 60, 120, and 180 kg N ha$^{-1}$ for wheat and 0, 100, 200, and 300 kg N ha$^{-1}$ for maize. The observed aboveground biomass shown in dashed lines in (b) represents the mean values from 1993 to 2008. Abbreviations: NoTill—no tillage; Till—Tillage; RR—100% of main-crop residue retention; M—maize; W—wheat; SF—sunflower; MCRs—main crop residues; CCs—cover crops.

Shoot biomass and N mass of the $C_3$ herbaceous CCs in our simulations first increased rapidly between October and November, and then commenced again in late March in response to the increasing temperature in spring (Figure 4a). With exception of 2008, the modeled aboveground production of CCs was lower than the field measurements; differences between modeled and measured were 0.7 and 0.5 *t* ha$^{-1}$ in 2007 and 2009, respectively. Over the cropping seasons there was an underestimation of maize yield for all simulations, ~15%–26% lower than the observed values of 11.2–11.7 *t* ha$^{-1}$ (Figure 4a). Replacing bare fallows with CCs was simulated to reduce maize production by 6%–8%, in line with the observed loss of 1%–4%, likely reflecting indirect competition for water and nutrients between CCs and main crops. These negative impacts of CCs on yield were also found in the field-grown soybean trials (reduction of 1%–13%) but not found in our model experiments (Figure 4a).

The simulated nitrate leaching from bare fallow cropland (NoCC) ranged from 32 to 95 kg N ha$^{-1}$ yr$^{-1}$ during 2006–2009 (with a total cumulative loss of 219 kg N ha$^{-1}$ until 2009; Figure 4b), and exceeding the observed values of 29–67 kg N ha$^{-1}$ yr$^{-1}$ over the same period (195 kg N ha$^{-1}$ in total; Kaspar et al., 2012). Using CCs mitigated this hydrological N loss by 35%–75% to 9–37 kg N ha$^{-1}$ in the field trials, comparable but higher than our modeled reduction of 13%–34%. The cause for the underestimated reduction in N leaching may be that the simulated soil N uptake by CCs was lower than the field measurements, given that shoot N mass of CCs was

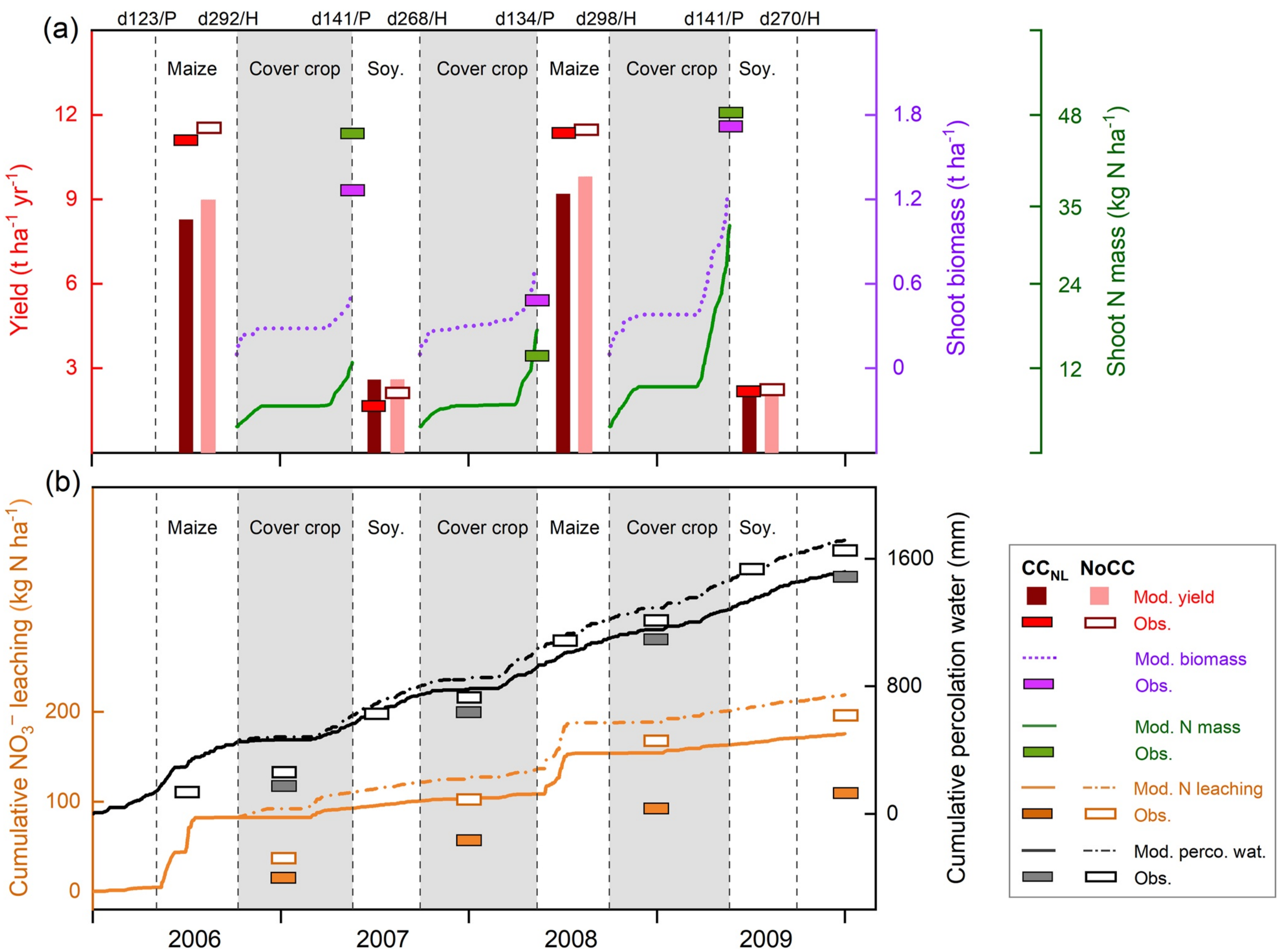


**Figure 4.** Modeled and observed shoot biomass and shoot N mass of cover crops, and main crop yield (a) in a rain-fed maize-soybean rotation system in Ames (USA) from 2006 to 2009, and the response of cumulative percolation water and nitrate leaching to cover crop practice compared to the control treatment with bare fallows (b). The observations from overwintering cover crops(ryegrass) reported in Kaspar et al. (2012) were chosen for model evaluation. Maize during the growing season received 225 and 198 kg N ha$^{-1}$ of fertilizer application in 2006 and 2008, respectively, and no chemical N fertilizer was applied to soybean over the entire experimental period. Abbreviations: NoCC—control treatment with bare fallows; CC$_{NL}$—non-legume cover crops; d—day of the year; P—planting date of main crops; H—harvest date of main crops; Soy—soybean.

below the observations (Figure 4a). Step changes in simulated N leaching over the cropping seasons 2006 and 2008 (Figure 4b) corresponded to the high fertilization rates of 198–225 kg N ha$^{-1}$ in maize systems. Such an increase was absent in 2007 and 2009 mainly because soybeans were not fertilized. In addition, the replacement of bare fallows with CCs in our simulations had the potential to reduce soil percolation water by 3%–12%, agreeing well with the observed decreases of 4%–20% (Figure 4b).

### 3.2. Global Crop Ecosystem Responses to Cover Crops

#### 3.2.1. Soil Carbon Stocks

Our simulations of the three explored CC managements resulted in a net soil C increase across global croplands compared with the control treatment (NoCC), with the largest SOC sequestration rates ($\Delta SOC_{rate}$, Equation 4) found in warm and moist regions (Figure 5 and Figure S4 in Supporting Information S1). For the 36-year simulation period, the maximum annual rates of soil C sequestration in the CC$_{NL}$ and CC$_L$ runs were reached in the sixth year after introducing cover cropping, whereas in the CC$_L$NT simulation they were already achieved in the fourth year after the implementation of altered management (Figure 5). After these initial peaks, the annual soil C accumulation effect persisted over the course of the remaining simulation period, but with declining rates. On

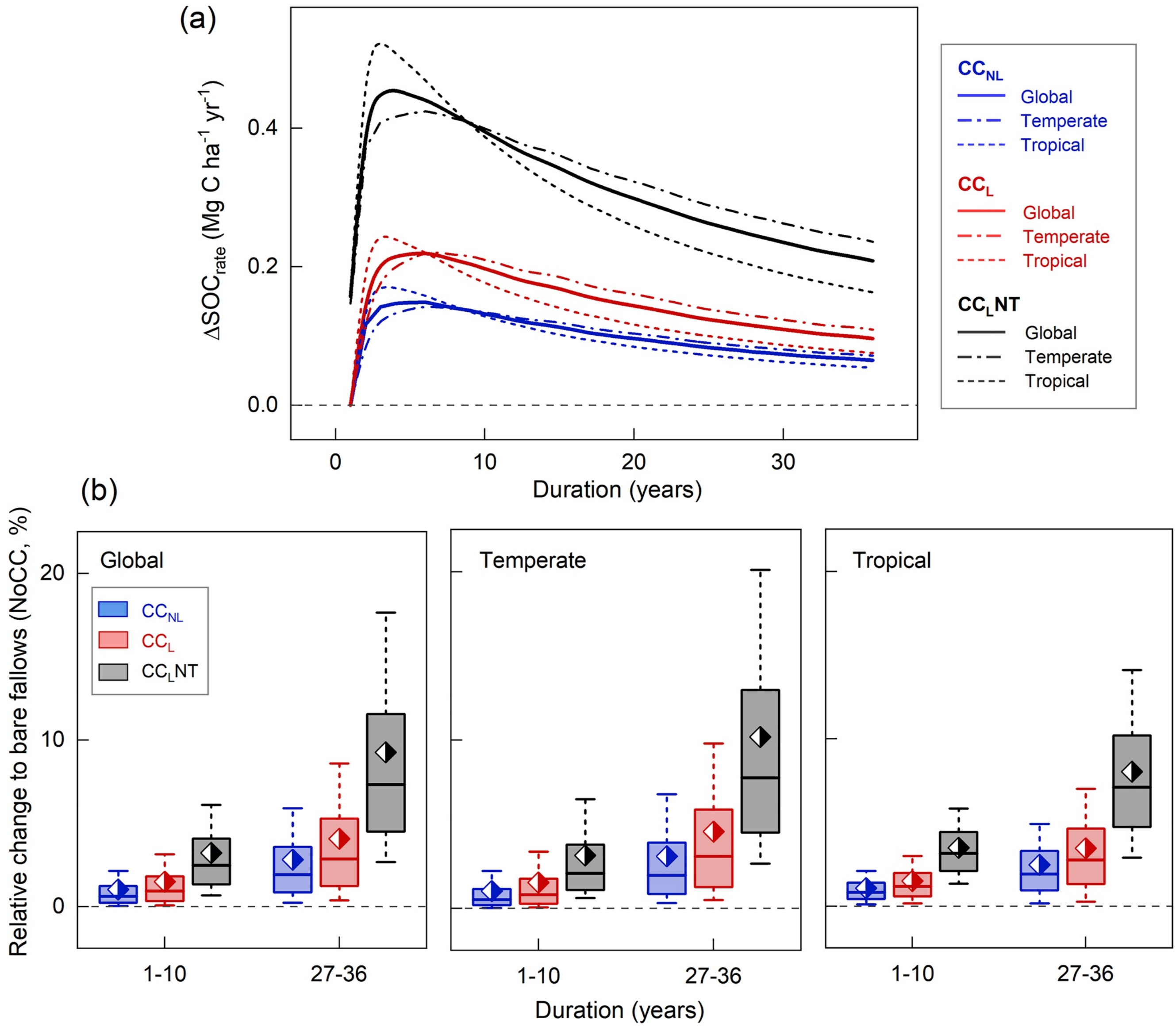


**Figure 5.** Area-weighted aggregated average annual soil C sequestration rate (Equation 4, Mg C ha$^{-1}$ yr$^{-1}$) across global (1,597 × 10$^6$ ha), temperate (987 × 10$^6$ ha), and tropical (606 × 10$^6$ ha) croplands for three cover crop managements ($CC_{NL}$: blue; $CC_L$: red; $CC_L$NT: black) in the $CA_{all}$ scenario (a), and relative responses (%) of soil organic carbon stocks to these cover crop strategies compared with the control treatment (bare fallows, NoCC) in the first and last decades of the 36-year simulation period (b). The temperate region in this study is defined as the latitudes from 23.5° to 60° N/S of the equator, and latitudes between 23.5°S and 23.5°N are classified as the tropics. Box plots in (b) denote the 5th and 95th percentiles with whiskers, median and interquartile range with box lines, and mean with diamonds across all cropland grid cells (global:35,039; temperate:21,223; tropical:12,942).

average, using CCs was modeled to sequester 0.10, 0.14, and 0.32 Mg C ha$^{-1}$ yr$^{-1}$ of soil carbon in the $CC_{NL}$, $CC_L$, and $CC_L$NT runs, respectively (Figure 5).

Under the $CA_{all}$ scenario, modeled total soil C stocks (0–150 cm) of the various managements ranged from 164.9 to 176.4 Pg C across global croplands, somewhat larger than the published estimates for the topsoil layer (140 Pg C in 0–30 cm, Zomer et al., 2017; 115 Pg C in 0–50 cm, Ren et al., 2020) and within the reported values for the depth 0–100 cm ranging between 157 and 164 Pg C (Global Soil Data Task, 2014; Jobbágy & Jackson, 2000) and 210 Pg C (for 0–200 cm; Jobbágy & Jackson, 2000). In comparison with bare fallows (NoCC), simulations from LPJ-GUESS resulted in an increase of soil C storage by 3.8 (+2.3%) and 5.4 Pg C (+3.3%) after 36 years of implementation of non-legume ($CC_{NL}$) and legume cover crops ($CC_L$), respectively, between the main cropping seasons. Adopting no tillage ($CC_L$NT) further contributed to increasing modeled C storage by 11.5 Pg C (+7.0%) across global croplands ($CA_{all}$ scenario; Table 2).

**Table 2**
*Modeled Total Cropland Soil Organic Carbon Stocks (0–150 cm), N Leaching Loss, and Crop Production With Alternative Cover Crop Managements Under Three CA Area Scenarios in the First and Last Simulated Decades, Compared With Literature-Based Estimates*

| | | Soil C stock, total (Pg C) | | N leaching, total (Tg N yr$^{-1}$) | | Crop production[b] (million tonnes per year) | |
|---|---|---|---|---|---|---|---|
| Scenario[a] | Management | 1–10 years | 27–36 years | 1–10 years | 27–36 years | 1–10 years | 27–36 years |
| $CA_{his}$ (126 × 10$^6$ ha) | NoCC | 15.8 | 15.6 | 0.88 | 0.80 | 301 | 287 |
| | $CC_{NL}$ | 15.9 | 15.9 | 0.52 | 0.49 | 286 | 292 |
| | $CC_L$ | 16.0 | 16.1 | 0.58 | 0.54 | 295 | 306 |
| | $CC_L$NT | 16.2 | 16.7 | 0.51 | 0.48 | 279 | 294 |
| $CA_{pot}$ (590 × 10$^6$ ha) | NoCC | 68.9 | 68.0 | 5.2 | 5.4 | 1,145 | 1,126 |
| | $CC_{NL}$ | 69.4 | 69.5 | 3.3 | 3.2 | 1,068 | 1,119 |
| | $CC_L$ | 69.6 | 70.2 | 3.7 | 3.6 | 1,105 | 1,172 |
| | $CC_L$NT | 70.3 | 72.5 | 3.2 | 3.2 | 1,034 | 1,125 |
| $CA_{all}$ (1,597 × 10$^6$ ha) | NoCC | 167.3 | 164.9 | 18.4 | 17.8 | 2,785 | 2,743 |
| | $CC_{NL}$ | 168.5 | 168.7 | 10.8 | 10.5 | 2,635 | 2,765 |
| | $CC_L$ | 169.1 | 170.3 | 12.2 | 11.7 | 2,714 | 2,875 |
| | $CC_L$NT | 171.1 | 176.4 | 10.7 | 10.5 | 2,557 | 2,780 |
| Other studies (global cropland) | | 115[c]; 140[d]; 157–210[e]; 164[f] | | 14–20[g]; 23[h]; 26[i]; 31[j] | | 2806[k] | |

[a]See Figure S2 in Supporting Information S1 for spatial pattern of three CA area scenarios. [b]Summed yield of four crop types: maize, wheat, rice, and soybean. [c]Ren et al. (2020), 0–50 cm, 1,667 × 10$^6$ ha. [d]Zomer et al. (2017), 0–30 cm, 1,631 × 10$^6$ ha. [e]Jobbágy and Jackson (2000), the estimate for 0–100 cm is 157 Pg C, and that for 0–200 cm is 210 Pg C, 1,400 × 10$^6$ ha. [f]Global Soil Data Task (2014), 0–100 cm, 1,518 × 10$^6$ ha. [g]Smil (1999). [h]J. Liu et al. (2010). [i]Lin et al. (2001). [j]Q. Liu et al. (2019). [k]FAOSTAT (2023); reported total production in the year 2014 were used for comparison: 1,040, 729, 731, and 306 million tonnes for maize, wheat, rice, and soybean, respectively.

### 3.2.2. Cropland N Leaching and Yields

In addition to soil C benefits, CCs resulted in a reduction in simulated N leaching in most global croplands (i.e., $CA_{all}$ scenario), with the largest decreases (∼75%–90%) found in Russia and large parts of Africa, regions where mineral N fertilizer application were rather low (Figure S1 in Supporting Information S1). Modeled N leaching reduction in response to CCs in China, Western Europe, and the United States—areas with substantial fertilizer application (Figure S1 in Supporting Information S1)—were still 0%–45% for the 36-year simulation period (Figure 6). Our simulated total nitrogen loss of 17.8–18.4 Tg yr$^{-1}$ from fallow cropland (NoCC) was in good agreement with statistics-based estimates of 14–23 Tg N yr$^{-1}$ (J. Liu et al., 2010; Smil, 1999), but lower than the findings of 26–31 Tg N yr$^{-1}$ in Lin et al. (2001) and Q. Liu et al. (2019) who uses a modeling approach (Table 2). Replacing bare fallows with cover cropping across global croplands was modeled to reduce N leaching by 7.3–7.6 and 6.1–6.2 Tg N yr$^{-1}$ in the $CC_{NL}$ and $CC_L$ runs, respectively. The latter (i.e., $CC_L$) was ∼17% lower than the decreases of 7.3–7.7 Tg N yr$^{-1}$ from $CC_L$NT (Table 2, Figure 6), supporting arguments for practicing conservation tillage techniques to mitigate hydrological N losses.

The modeled impacts of legume cover crops ($CC_L$) on yields of the main crops showed large spatial variation (Figure 7; see Figure S5 in Supporting Information S1 for the spatial patterns of $CC_{NL}$ and $CC_L$NT). Small, and inconclusive with respect to their direction, yield changes between −5% and 5% (36-year average) were found in China across all crop types, likely as a consequence of the high N fertilizer input (Figure S1 in Supporting Information S1). A widespread yield loss in response to CCs was seen in northern cold and temperate dry climates, whereas yields in humid regions—such as the eastern USA, southern China, and most of South America and Africa—increased (Figure 7), reflecting high biomass and high N fixation rates (Figure S6 in Supporting Information S1). However, these modeled impacts varied widely between different cropping systems, with the largest yield variability found in maize and wheat, followed by rice. Productivity of soybean crops responded only little to legume CCs (Figure 8).

Our model simulations under bare fallow management (NoCC) resulted in a total crop production of 2,743–2,785 million tonnes yr$^{-1}$ globally, consistent with FAO-reported estimate of 2,806 million tonnes in the year 2014 (Table 2), implying the reliability of the current model version to reproduce food production at the global scale.

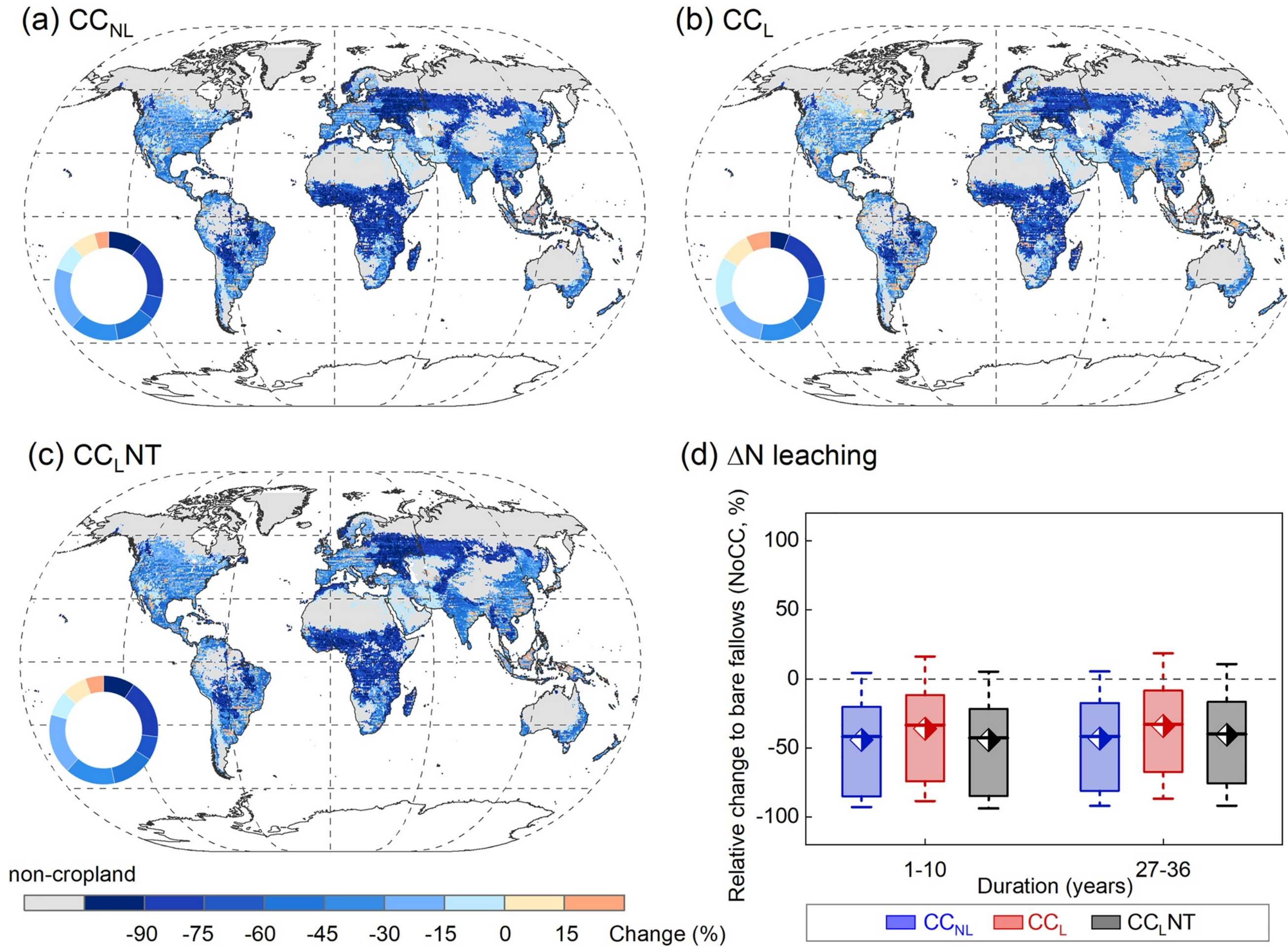


**Figure 6.** Maps of the simulated responses (%, 36-year average) of cropland N leaching to CC$_{NL}$ (a), CC$_L$ (b), and CC$_L$NT (c) managements, relative to the control treatment with bare fallows (NoCC) in the CA$_{all}$ scenario. Box plots of these responses in the first and last simulated decades are shown in (d), denoting the 5th and 95th percentiles with whiskers, median and interquartile range in box lines, and mean with diamonds across all cropland grid cells (35,039). The inset donut plots in (a–c) represent the area proportion of each classified Δ*N* leaching from the total cropland area.

Compared with fallow soils during off-season period, using CCs was modeled to potentially reduce main-crop yield in the first decade for the 36-year simulation, with mean decreases of 6%, 3%, and 8% in CC$_{NL}$, CC$_L$, and CC$_L$NT, respectively. However, these negative yield effects were gradually diminished over the course of simulation, and turned to positive impacts in the last decade, with slight production increases of 1%–5% simulated for the three assessed managements in comparison with the control treatment (Table 2).

## 4. Discussion

### 4.1. Soil Carbon Stocks

LPJ-GUESS simulates cropland soil carbon stocks across all the evaluated sites well, although the measured SOC increase in response to CCs is generally underestimated (Figure 2). One likely explanation for this discrepancy is the low biomass production of CCs in the model experiments (Figures 3 and 4), resulting in less C input to the soil pools compared to the field measurements. Experimental evidence from the field sites has shown that the amount of biomass C added to the soil through CCs varies widely between cover crop species (Constantin et al., 2010; Kuo et al., 1997; Sainju et al., 2002). Using two grass functional types (i.e., groups of grasses with similar functional behaviors; see Section 2.2) to represent all cover crop situations in our standardized evaluation cannot reflect this variability. Also, when comparing herbaceous CC effects on soil carbon stocks, belowground C input via roots has been proven to stably enhance SOC sequestration in the field measurements (Blanco-Canqui

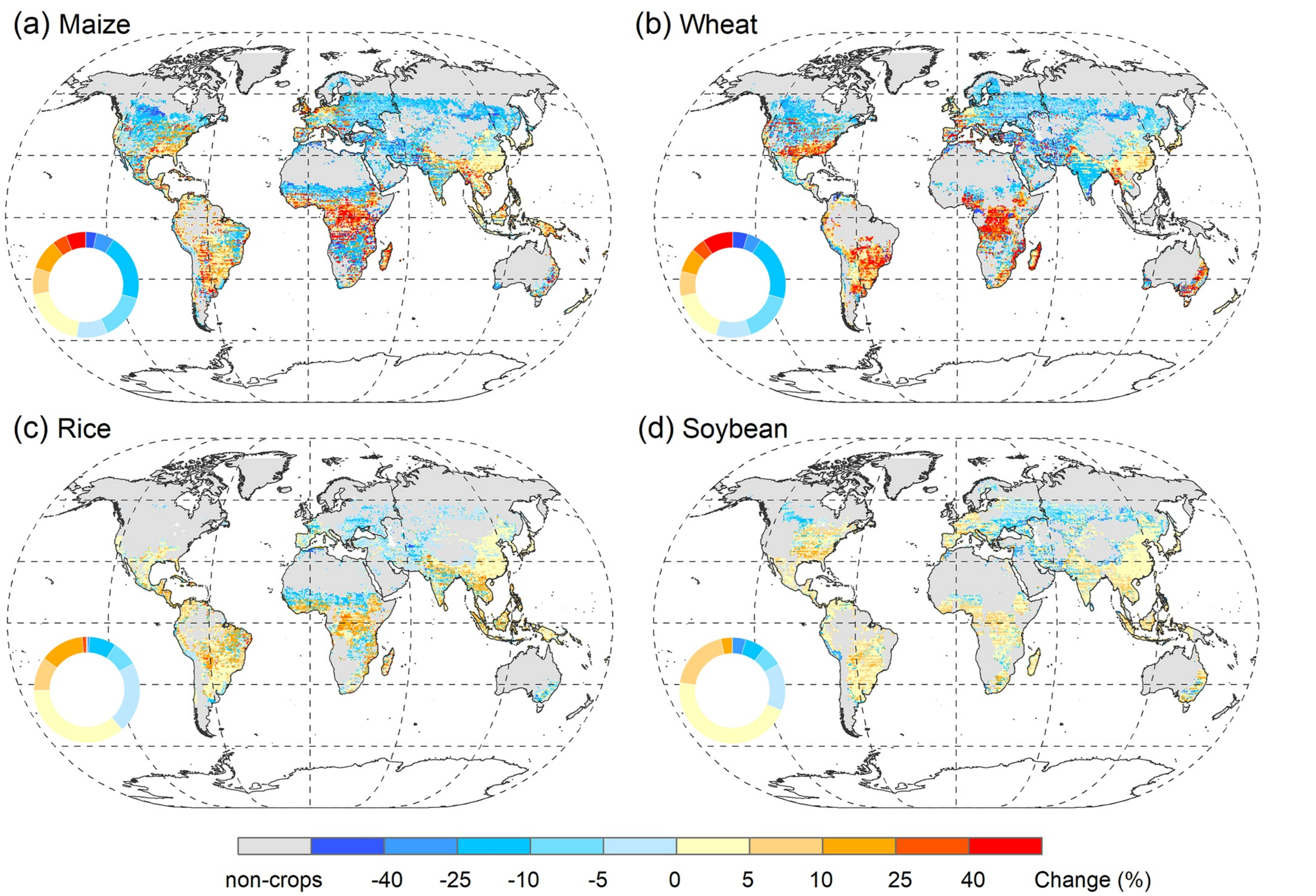


**Figure 7.** Maps of simulated crop-specific production in response to legume cover crops ($CC_L$) compared to the control treatment with bare fallows (NoCC) in the $CA_{all}$ scenario: maize (a), wheat (b), rice (c), and soybean (d). Modeled crop-specific production at each grid cell is calculated as the area-weighted aggregated results in rain-fed and irrigated conditions. Global total cropping areas (rain-fed and irrigated) in the year 2014 used in this study are 184.5, 247.7, 151.7, and 95.9 × $10^6$ ha for maize, wheat, rice, and soybean, respectively, with rain-fed proportions of 84%, 77%, 44%, and 94% for those four crop types. Yield relative changes (%) in maps are given as the mean values for the 36-year simulation period. The inset donut plots represent the area proportion of each classified Δyield from the total crop-specific area.

et al., 2015; Rasse et al., 2005) but with large variability due to differences in soil types, local climate, and CC species (Sainju et al., 2017). For instance, in a 2-year U.S. trial, Kuo et al. (1997) found that the root-to-shoot ratio of plant biomass C grown under natural conditions ranged from 0.5 to 0.8 for ryegrass (non-legume) and 0.2–0.5 for hairy vetch (legume). In comparison, higher root-to-shoot ratios in perennial grasses (e.g., intermediate wheatgrass and smooth bromegrass) ranging from 1.0 to 3.5 were reported in another U.S. field experiment with continental climate, depending on soil sampling depth and nutrient availability (Sainju et al., 2017). Here, we implemented a prescribed root-to-shoot ratio of 2.0 to broadly represent below- and aboveground biomass productions in herbaceous plants based on literature values (see Section 2.2). Whether this set value affects the simulated root-derived carbon from CCs is difficult to assess because root biomass information was typically unavailable from the test sites. In addition, at this point LPJ-GUESS does not account for potential C inputs through weeds (Figure 3; Mazzoncini et al., 2011), which may further bias our assessed CC effects on SOC sequestration rates at site scale.

Our modeled global-scale small SOC increase of 1.0%–2.8% for non-legume cover crops ($CC_{NL}$) and 1.5%–4.1% for legumes ($CC_L$) (Figure 5) agreed with the meta-analysis of Abdalla et al. (2019) and Poeplau and Don (2015), in which replacing bare fallows with CCs statistically showed no significant difference between cover crop types for SOC sequestration, with a mean increase of 4.1% and 4.5% found for non-legumes and legumes, respectively. However, these reported impacts were somewhat lower than a recent synthesis conducted by Jian et al. (2020), who found that cover cropping would result in a net SOC sequestration of 0.56 Mg C $ha^{-1}$ $yr^{-1}$ with all cover

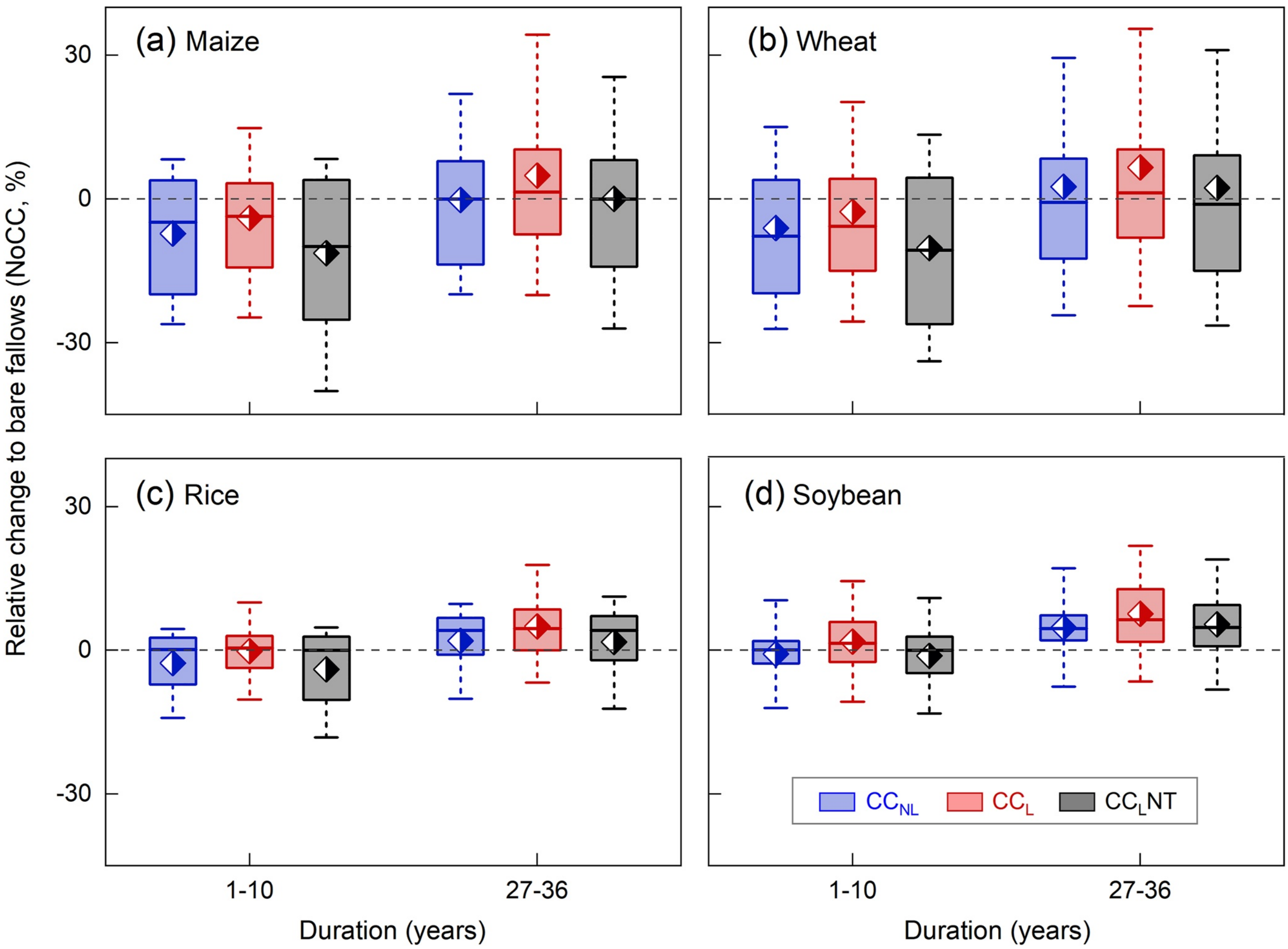


**Figure 8.** Box plots of the simulated crop-specific production in response to three cover crop managements ($CC_{NL}$: blue; $CC_L$: red; $CC_LNT$: black), compared to the control treatment with bare fallows (NoCC) in the first and last simulated decades under the $CA_{all}$ scenario: maize (a), wheat (b), rice (c), and soybean (d). Modeled crop-specific production at each grid cell was calculated as the area-weighted aggregated results in rain-fed and irrigated conditions. Box plots of yield relative changes (%) denote the 5th and 95th percentiles with whiskers, median and interquartile range with box lines, and mean with diamonds across all crop-specific grid cells (maize: 31,635; wheat: 27,126; rice: 21,598; soybean: 23,306).

crop types included, ~15.5% higher than the bare-fallow control treatment. In our model experiments, only the combined agricultural practice, that is, legume CCs and no tillage ($CC_LNT$), produced a mean SOC increase of 9.7% after a 36-year simulation (Figure 5), which is more comparable to but still below the findings in Jian et al. (2020). The discrepancy between the global simulation and site-level field experiments likely reflects their difference in the investigated geographical scales and land-use history, as well as to the diverse managements and methodologies among field studies (such as CC species, retained residue proportion, and implementation duration). Nevertheless, the potential of obtaining higher SOC stocks via cover crop management seems realistic, even though the exact magnitude of the effect remains unresolved.

In the global experiment, the annual SOC sequestration rate was modeled to be largest in the early years after introduction of CCs, and it then gradually declined over the course of the remaining simulation period (Figure 5), similar to published findings. Sommer and Bossio (2014) reported annual SOC stock changes in response to the improved agricultural practices approaching a maximum between the third and seventh year after adopting soil-conserving techniques and a subsequent decreasing trend for 15–20 years. A meta-analysis of tropical crop ecosystems also indicated reduced SOC sequestration rates (after an initial peak) to persist for 4–25 years until a new SOC equilibrium state was reached, but the duration was highly dependent on climates and soil types (Powlson et al., 2016). In our model experiments, at the end of 36-year simulation the continued trends indicate that a new steady state in soil C and N pools had not yet been achieved, which was similar to results in Porwollik

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et al. (2022), who found no dynamic steady state after 50 years of simulation with the LPJmL model in response to planting herbaceous CCs on global cropland during fallow period.

In our study we attempted to quantify the contribution of CCs to enhancing soil C pools globally, which could also be interpreted as a climate change mitigation measure. After 36 years of implementation, using two herbaceous CCs was found to sequester ∼0.01 Pg $yr^{-1}$ soil carbon across the simulated 126 × $10^6$ ha cropland ($CA_{his}$ scenario, ∼8% of current cropland areas worldwide; Table 2). If all agricultural lands were to adopt cover crop practices ($CA_{all}$ scenario), the SOC sequestration potential could be as high as 0.11, 0.15, and 0.32 Pg C $yr^{-1}$ (i.e., 0.40, 0.55, and 1.17 Pg $CO_2$ $yr^{-1}$) for non-legumes ($CC_{NL}$), legumes ($CC_L$), and the combined agricultural practice ($CC_L$NT), respectively, compensating for 8%–22% of annual direct GHG emissions from crops and livestock activities (5.3 Pg $CO_2$eq $yr^{-1}$; FAO, 2020), or equivalent to 10%–29% of GHG emissions from agricultural land use change (4.0 Pg $CO_2$eq $yr^{-1}$; FAO, 2020). Planting anywhere near 100% of global cropland with CCs is impractical for a number of reasons: a large share of agricultural area used for winter crops (Kaye & Quemada, 2017; Poeplau & Don, 2015), potential water limitations or too low winter temperature during off-season periods (Dabney et al., 2001), and insufficient growing windows for CCs in multi-cropping systems in the tropics (Hu et al., 2018; Zhu et al., 2012). Nevertheless, these estimates from our simulations do provide an upper bound for the amount of atmospheric carbon that might be sequestered through cover crop cultivation. Under the more realistic adoption scenario of $CA_{pot}$ (590 × $10^6$ ha, ∼37% of current cropland areas; Table 2), carbon taken up in response to individual cover crop practices (0.15 and 0.22 Pg $CO_2$ $yr^{-1}$ for $CC_{NL}$ and $CC_L$, respectively) and the combined conservation management ($CC_L$NT; 0.46 Pg $CO_2$ $yr^{-1}$) could approximately offset 3%–9% of direct yearly GHG emissions from crops and livestock activities. However, additional N inputs to the soil from CCs could also potentially offset the $CO_2$ mitigation effect on the field scale as these would lead to increased $N_2O$ emissions (Lugato et al., 2018; Quemada et al., 2020). Whether such a trade-off between soil carbon and nitrogen GHG fluxes due to cover cropping would emerge at the global level was not considered in this study and thus needs to be quantified in future modeling work.

### 4.2. N Leaching

Both model and field experiments showed that N leaching from cropland ecosystems was strongly associated with N management: applying chemical fertilizer resulted in higher hydrological N loss compared with the unfertilized treatments (Figure 4 and Figure S3 in Supporting Information S1), likely a consequence of the enhanced size of the nitrate pool. However, several disagreements between simulated and measured N leaching were found for some field trial locations despite similar N fertilizer inputs (Figure 2 and Figure S3 in Supporting Information S1), indicating that other factors, such as soil texture type, climate condition, or throughflow, are at play as well. For example, two of the field experiments included in our analysis sites showed a decreasing trend in total N leaching (mineral plus organic) from coarse-, medium-, to fine-textured soils (Aronsson et al., 2011; Lemola & Turtola, 2000). When testing our simulation setup at these two locations, the reported soil texture effect was not captured well by the model (not shown), suggesting that the N leaching representation in LPJ-GUESS should be further improved. Moreover, compared with observations, the overall smaller reduction in N leaching in response to the simulated CCs (Figure 2) might be partially attributed to the underestimated biomass of CCs (Figures 3 and 4), which would also underestimate plant N demand and soil N uptake. In addition, since the model cannot simulate two plants growing at the same time (see Section 2.3.1), the total length of the undersown-CC growing period in our simulations was approximately 1–2 months shorter than the field trials across all northern European sites (Table S3 in Supporting Information S1), which further limited cover crop capacity for uptake of excess N remaining in the soil column in the model.

Compared with the bare-fallow setup, mean decreases of 41% and 34% in N leaching were simulated across the globe in response to the experiment with non-legume ($CC_{NL}$) and legume cover crops ($CC_L$), respectively (Table 2), close to the lower end of the wide reported reduction range between 30% and 70% in the literature (Abdalla et al., 2019; Nouri et al., 2022; Quemada et al., 2013; Thapa et al., 2018; Tonitto et al., 2006). The reduction in N leaching due to CCs partially reflects the decreases in leachate volume and soil reactive N concentration because of enhanced water and N uptake by CCs during their growth (Thapa et al., 2018). This process may also underlie the smaller decreases in N leaching under N-fixing CCs compared with non-legumes for both field measurements (Abdalla et al., 2019; Nouri et al., 2022) and model simulations ($CC_{NL}$ vs. $CC_L$). Where biological N fixation is the dominant N source for leguminous plants, it diminishes the capacity for mineral N uptake from soils (Fontaine et al., 2022). Moreover, including the no-till technique in cover cropping in our simulations had the potential to further mitigate N leaching (41% in $CC_L$NT vs. 34% in $CC_L$; Table 2) mainly due to the reduced net N mineralization rates (Figure S7 in Supporting Information S1). This is in line with the findings from a meta-analysis by Thapa et al. (2018) and a recent modeling study by Porwollik et al. (2022).

Globally, the largest percent decreases in N leaching due to CCs were modeled in regions with relatively little N fertilizer use (such as Russia and large parts of Africa; Figure 6 and Figure S1 in Supporting Information S1), where soil reactive N pools were small. Results from a 6-year field experiment implemented by Wittwer et al. (2017) also showed that the effectiveness of CCs in reducing N leaching decreased with management intensity (e.g., tillage regimes and fertilizer application rates). This effect underlies discrepancies at some national borders, such as Indonesia and Papua New Guinea (Figure 6), countries with similar climates but with contrasting fertilizer applications (Figure S1 in Supporting Information S1). Likewise, in some arid and semi-arid regions, as well as temperature-limited areas in the high latitudes (e.g., Canada) a slight decrease of N leaching in response to cover cropping systems was found, as poor growth conditions constrained the CC capacity for soil N uptake. In addition, the rapid turnover rate of SOM pools driven by warm and moist climate (Olin, Lindeskog, et al., 2015), together with abundant precipitation may increase N leaching with cover crop practices in the humid tropics (Figure 6) as a result of high biomass of N returned to soils (Figure S6 in Supporting Information S1) and enhanced throughflow (Porwollik et al., 2022).

### 4.3. Crop Yields

Accounting for the impacts of management practices, particularly regarding water and N limitations to crop growth in LPJ-GUESS, resulted in a good agreement between simulated and observed crop yields across different field trials despite some outliers in rice and wheat systems (Figures S3 and S8 in Supporting Information S1). For both modeling and field-based experiments, yields in the main crops following non-legume CCs declined, although the overall difference from fallow controls (NoCC) was small (Figure 2b). The difference between periods of soil N mineralization and high N demand of main crops (Marcillo & Miguez, 2017), and enhanced soil N immobilization shortly after the planting of non-legume CCs (Abdalla et al., 2019; Erenstein, 2003) may contribute to the declines in yields of the main crops in the field experiments. In comparison, N-fixing CCs with relatively low C:N ratios are expected to stimulate soil N release during their decomposition, enhancing plant-available N in soils (Li et al., 2020; Quemada et al., 2013; Thapa et al., 2018). This was in line with our model findings, wherein legume CCs generally resulted in higher net N mineralization rates than non-legumes (Figure S7 in Supporting Information S1) and thus increased the productivity of the main crops in some cases (Figure 2b). However, it should be noted that these CC effects were highly dependent on cropping systems, with little impact found on productivity of soybeans (Table S5 in Supporting Information S1). This is likely due to their N fixation capacity, which diminished the N competition between CCs and soybeans in both field trials and model simulations.

Our modeled global mean yield losses due to CCs in the first decade of the simulations (−3% for $CC_L$ and −6% for $CC_{NL}$; $CA_{all}$ scenario in Table 2) compared well with a recent meta-analysis by Garba et al. (2022), who reported a mean crop production change of −4.9% and −10.1% for legume and non-legume CCs, respectively, after 2–17 years of management. Main-crop yield reduction under cover cropping systems likely reflected (a) the indirect competition for water and nutrients between CCs and subsequent main crops (Valkama et al., 2015), and (b) the time that soil SOM pools need to adjust to management shifts (Figure 5 and Figure S7 in Supporting Information S1). Garba et al. (2022) also pointed out that cover cropping systems under the no-till practice resulted in lower main-crop yields compared with conventional tillage, in line with our model findings in terms of total crop production worldwide ($CC_L$NT vs. $CC_L$; Table 2). However, at least in our simulations, these negative yield effects induced by conservation tillage may be mitigated over the course of the simulation (Table 2) because of the gradual stabilization of soil C and N pools over time (Figure 5 and Figure S7 in Supporting Information S1). A similar finding from a meta-analysis by Pittelkow et al. (2015) indicated that yield benefits, globally, in cereal- and legume-based cropping systems may be attained after 10+ years of conversion from conventional tillage to no-till management.

N fertilizer application was found to be another factor that influenced the effectiveness of CCs on subsequent crop yields for both site-level (Figure S3 in Supporting Information S1) and large-scale simulations (Figure 7). The smallest impacts on main-crop production were found for well-fertilized cover cropping systems, consistent with previous field-based reviews (Daryanto et al., 2018; Marcillo & Miguez, 2017; Quemada et al., 2013; Tonitto et al., 2006; Zhao et al., 2022), since enhanced soil mineral N pools driven by fertilization reduce the N competition between CCs and main crops. This can explain the small yield penalty (or benefit) from cover cropping in soybean (Figures 7 and 8), which is a nitrogen fixer and experiences less N stress during the growing season compared with cereal crops. Likewise, the spatial variability regarding CC impacts on rice production was also much smaller than simulated maize and wheat CFTs (Figures 7 and 8), primarily because rice in our simulations was mostly irrigated (Figure 7), which reduced water limitation on crop growth caused by CCs in rice-producing areas. Furthermore, the broadly negative impacts of CCs on simulated yields in northern temperate climatic regions (Figure 7) can be attributed to the slow decomposition of SOM in response to low temperature, where the N retained in the SOM is released evenly throughout the year and not easily available for main crop uptake after CC growth (Olin, Lindeskog, et al., 2015). In contrast and as discussed above, plant materials from CCs in the humid tropics are expected to rapidly decompose due to the fast turnover rate, continuously releasing reactive N for plant uptake in the next cropping season and therefore enhancing main-crop productions. This contrasting spatial difference in yield changes between temperate and tropical climates supports a meta-analysis finding that cultivating CCs during bare-fallow period, on average, has a risk to reduce main-crop productivity by ∼12% in temperate agricultural soils while gaining ∼15% of yield benefits in the tropics (Garba et al., 2022).

### 4.4. Modeling Limitations and Implications

A detailed evaluation of modeling CC impacts on cropland worldwide remains a challenge due to various cover crop species, farming rotation systems, and managements in the field trials. We mainly examined the model performance via categorizing herbaceous CCs as non-legume and legume functional types, with site-specific management practices considered (Tables S2–S4 in Supporting Information S1). Although the current C-N version of LPJ-GUESS can reproduce the observed responses of ecosystem service indicators to CC cultivation, the magnitude of these changes did not always match experimental measurements (Figure 2, Table S5 in Supporting Information S1). This likely reflects the differences between highly controlled field conditions and model's representation of management history, initial SOM levels, cropping system management, and the C-N allocation scheme in CCs. In addition, important processes that determine CC impacts in the field experiments—such as occurrence of weeds (Mazzoncini et al., 2011), intercropping (Valkama et al., 2015), termination methods of CCs (Bloszies et al., 2022); erosion (Daryanto et al., 2018), and soil structural modification via grass roots (Nouri et al., 2022)—have not been accounted for in the model.

To compare model outputs with observations, as introduced in Section 2.4, we standardized the measured SOC from the original depth to the modeled depth of 150 cm using an empirical depth distribution function. There are large uncertainties associated with these extrapolated SOC stocks due to the varying management effects on soil C pools with depth. For example, a global meta-analyses is found SOC benefits of no-till farming to be statistically significant in the topsoil (0–15 cm) and decline with soil depth (Haddaway et al., 2017). Scaling SOC stocks with a simple extrapolation function cannot reflect the observed variability in the field and thus our approach by necessity is a simplified one.

Legume CCs are usually identified as a promising strategy to substitute chemical N fertilizer in agricultural productions due to their high N fixation rates (Herridge et al., 2022; Peoples et al., 2021). Our modeled N fixed by natural $C_3$ grass (a surrogate for white clover; see Text S1 in Supporting Information S1) during main-crop off-season periods are 30–70 kg N ha$^{-1}$ yr$^{-1}$ in warm and moist regions (36-year average; Figure S6 in Supporting Information S1), which are lower than the reported range of 49–154 kg N ha$^{-1}$ yr$^{-1}$ but these latter estimates were for the entire year (Anglade et al., 2015; Burchill et al., 2014; Ledgard et al., 2001). Nonetheless, in our simulations employing legume CCs results in higher yield benefits in the humid tropics compared with non-legumes (Figure 7 and Figure S5 in Supporting Information S1). As described in Section 2.1, one main growing season within a year is modeled in LPJ-GUESS, total agricultural production achieved by multi-cropping systems in the tropics are not yet captured. As a consequence, the N fixation rate and biomass in legume CCs may be too high since we overestimate the length of the bare-fallow period for cover crop cultivation (Porwollik et al., 2022). Compared to controls with no CCs, such an overestimation would then be possibly reflected in high SOC sequestration rates and yield benefits in tropical climates.

The inclusion of the no-till technique in cover cropping is an effective practice under CA systems for mitigating climate change (Blanco-Canqui et al., 2015). This combined strategy in our study is also modeled as a win-win management option in terms of enhancing SOC stocks while reducing N leaching rates, despite the accompanying ~8% of decrease in total crop production when integrated over global cropland for the first simulated decade (Table 2). It should be noted that assessing the effects of no-till management on cropland N leaching remains uncertain. Some studies reported that conservation tillage can slightly reduce this hydrological N loss because of the diminished net N mineralization rates (Porwollik et al., 2022; Salahin et al., 2021; Thapa et al., 2018). However, other studies found enhanced nitrate leaching in the reduced-tillage soils compared with conventional tillage systems, mainly due to the enhanced water drainage caused by greater abundance of macropores (preferential flow channels) and better soil infiltrability (Daryanto et al., 2017). It remains unknown which of these two processes played a more important role in the field trials, but the modifications of soil structural and hydraulic properties in response to tillage are not included in the version of the LPJ-GUESS used in this study.

Rather than planting herbaceous CCs, it is more common to use legume crops (e.g., faba bean and field peas) as "green manure" in some temperate regions (Andersen et al., 2020; Rinnofner et al., 2008). These grain legumes are usually intercropped with other cash crops, and incorporated to soils at full bloom stage to maximize N fixation rates while minimizing soil water depletion (Denton et al., 2017; Williams et al., 2014). To better represent region-specific cover crop practices, the implementation of N-fixing grain legumes as intercrops, together with multi-cropping systems within a year (see discussion above), remains to be taken into account in future model work.

## 5. Conclusions

In this study we developed a new $C_3$ grass functional type with biological N fixation in LPJ-GUESS to better account for legume CC effects on global crop ecosystems. The simulated C-N variables and main-crop productions in response to two herbaceous cover crop types (i.e., non-legumes and legumes) were widely evaluated against measured data from site level to global. Our model estimates demonstrated that crop ecosystems implemented in LPJ-GUESS realistically responded to non-legume and legume cover cropping under a range of water and N managements, and resulted in comparable C-N variables with observations, particularly for cropland SOC stocks.

When integrated over global croplands, our long-term simulations revealed that the impacts of CCs on agricultural soils can be beneficial for environmental sustainability without compromising crop production, particularly for the integrated management practice with legume CCs and no-till technique included. This combined strategy was modeled to achieve an annual SOC sequestration rate of 0.32 Mg C $ha^{-1}$ $yr^{-1}$ and to reduce N leaching by 41% (36-year average), also with a yield increase of 2% in the last simulated decade. The influence of CCs on crop production was strongly associated with main crop types and N fertilizer inputs, with small yield changes found in soybean systems and highly fertilized agricultural soils. Processes missing in the model, such as weeds, within-year multi-cropping systems, and cover crop management, may have biased our estimates of CC impacts on cropland globally.

The dynamic process of N fixation for grass CCs in LPJ-GUESS provides an opportunity to overall assess atmospheric carbon and nitrogen flows to agricultural lands during fallow periods, and thus is relevant for the estimates of global terrestrial C-N fluxes and pools under present-day and future climate, including how $CO_2$ uptake versus $N_2O$ emissions might interplay. It can also help to predict the possibility of substituting synthetic fertilizer with N-fixing green manure in global crop ecosystems, with various management strategies and climate conditions considered.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

Global historical climate data of GSWP3-W5E5 are available at https://doi.org/10.48364/ISIMIP.342217 (Lange et al., 2021). The monthly climate forcing data set of CRUJRA can be downloaded at https://data.ceda.ac.uk/badc/cru/data/cru_jra/cru_jra_2.1 (Harris et al., 2020; Kobayashi et al., 2015). National yield statistics of four crop types presented in this paper are from http://www.fao.org/faostat/en/#data (FAOSTAT, 2023). The site-level observations collected from the existing literature, together with large-scale model inputs and outputs as shown in the figures of this study, can be publicly accessed through the Zenodo repository at https://doi.org/10.5281/zenodo.7646911 (Ma et al., 2023).

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