Earth Syst. Dynam. Discuss., 6, 1047–1100, 2015
www.earth-syst-dynam-discuss.net/6/1047/2015/
doi:10.5194/esdd-6-1047-2015

Earth System Dynamics Discussions
Open Access

Soil carbon management in large-scale Earth system modelling: implications for crop yields and nitrogen leaching

S. Olin[1], M. Lindeskog[1], T. A. M. Pugh[2], G. Schurgers[3], D. Wårlind[4], M. Mishurov[1], S. Zaehle[5], B. D. Stocker[6], B. Smith[1], and A. Arneth[2]

[1]Department of Physical Geography and Ecosystem Science, Lund University, 223 62 Lund, Sweden
[2]Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research/Atmospheric Environmental Research, 82467 Garmisch-Partenkirchen, Germany
[3]Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen, Denmark
[4]CSIRO Sustainable Agricultural Flagship, CSIRO Agriculture, GPO Box 1666, Black Mountain, Canberra, ACT 2601, Australia
[5]Max Planck Institute for Biogeochemistry – Biogeochemical Integration Department, P.O. Box 60 01 64, 07701 Jena, Germany
[6]Department of Life Sciences, Imperial College London, Silwood Park, Ascot, SL5 7PY, UK

Received: 5 May 2015 – Accepted: 17 May 2015 – Published: 15 June 2015

Correspondence to: S. Olin (stefan.olin@nateko.lu.se)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

We explore cropland management alternatives and the effect these can have on future C and N pools and fluxes using the land use-enabled dynamic vegetation model LPJ-GUESS. Simulated crop production, cropland carbon storage, carbon sequestration and nitrogen leaching from croplands are evaluated and discussed. Compared to the version of LPJ-GUESS that does not include land use dynamics, estimates of soil carbon stocks and nitrogen leaching from terrestrial to aquatic ecosystems were improved.

We explore trade-offs between important ecosystem services that can be provided from agricultural fields such as crop yields, retention of nitrogen and carbon storage. These trade-offs are evaluated for current land use and climate and further explored for future conditions within the two future climate change scenarios, RCP 2.6 and 8.5. Our results show that the potential for carbon sequestration due to typical cropland management practices such as no-till and cover-crops proposed in literature is not realised, globally or over larger climatic regions. Our results highlight important considerations to be made when modelling C–N interactions in agricultural ecosystems under future environmental change, and the effects these have on terrestrial biogeochemical cycles.

1 Introduction

Growing population along with rapidly changing dietary preferences pose a key economical and environmental challenge of this century (Gerland et al., 2014; Hertel, 2015). According to estimates made by the United Nations Food and Agriculture Organisation (FAO), food production will need to be doubled by 2050 in order to meet the global food demand (FAO, 2008). Since the beginning of the 20th century there has been an increase in crop yields and overall production, especially since the 1950s (Steffen et al., 2015), as a result of agricultural intensification driven by substantial

ESDD
6, 1047–1100, 2015

advances in agricultural practices and technology, improved crop varieties and an increased application of N and P fertiliser (Evans, 1999; Spano et al., 2003). In addition, agricultural land area globally has expanded, with presently around 35 % of the total land surface being covered by cropland and pastures (Ramankutty et al., 2008). A further increase in cropland area by at most around 5 Mha (> 3 times the present area; Eitelberg et al., 2015) would be possible, but a range of societal and political pressures on land resources may limit the conversion of additional land area to agricultural production in many regions. Increasing yields on existing cropland would reduce pressure for further land conversion. Yield increases may be achieved through further development of high-yielding varieties or through further improvements in the efficiency of agricultural practices, the latter especially in regions where gaps between actual and potential yields are large (Licker et al., 2010; Mueller et al., 2014). The enhanced input of nitrogen (N) into ecosystems, jointly with other technical developments, has played a major role in the large increase in agricultural productivity over the last 50 years, often termed the "green revolution". However, the associated environmental effects have often been detrimental, with negative impacts on biodiversity and water quality, and substantial emissions of N trace gases that affect air quality and climate, such as nitrous oxide (N_2O), a potent greenhouse gas (Galloway et al., 2004; Rockstrom et al., 2009; Tilman et al., 2002; Vitousek et al., 1997). A large fraction of the N_2O emitted to the atmosphere today originates from terrestrial sources, mostly from fertiliser use on agricultural soils (Zaehle et al., 2011; Park et al., 2012; Ciais et al., 2013). Fertiliser use also promotes nitrate leaching which causes eutrophication and algal blooms in watersheds and coastal seas, with follow-on effects such as loss of fish populations and recreational value, and health risks through contamination of drinking water (Cameron et al., 2013). Even in Europe, where environmental regulations are relatively advanced, around 70 % of the population live in areas where the levels of nitrate in drinking water either exceed the recommended value (ca. 20 % of the population) or have reached at least half this level (ca. 50 % of the population; Grizetti, 2011).

ESDD
6, 1047–1100, 2015

Previous studies of the effects of agriculture on global biogeochemical cycles have typically focused on the largest immediate impacts, like the carbon losses following deforestation (e.g. Ciais et al., 2013; Houghton et al., 2012; Le Quéré et al., 2015). It is estimated that over the last 150–200 years, the conversion of natural to managed ecosystems, especially croplands, has released ca. 180 Pg carbon (C, current rate is $\sim 1\,\mathrm{Pg\,C\,yr^{-1}}$) from the terrestrial biosphere to the atmosphere by disturbing soils and through the harvesting and burning of biomass (Le Quéré et al., 2014). This sum is equivalent to around a third of the anthropogenic CO_2 concentration in the atmosphere today. However, the land-use related carbon flux is one of the most uncertain terms in the global carbon budget (Ciais et al., 2013; Le Quéré et al., 2015), and studies with dynamic vegetation models (DVMs) incorporating representations of land-use change (LUC) have shown that the actual estimate is highly dependent on the management practices assumed in the model (Bondeau et al., 2007; Levis et al., 2014; Lindeskog et al., 2013; Pugh et al., 2015).

Available knowledge on the effects of interactions between nitrogen and carbon cycles in terrestrial ecosystems is largely based on simulations with DVMs representing potential natural vegetation (e.g., Thornton et al., 2009; Zaehle and Dalmonech, 2011; Smith et al., 2014). The results obtained with these models suggest that soil N processes governing plant available nitrogen can constrain vegetation growth and the strength of the terrestrial carbon sink (e.g., Zaehle et al., 2011; Wårlind et al., 2014). Only two global modelling frameworks have been put forward with both detailed cropland ecosystem functioning and coupled C–N cycling simulated in a consistent fashion (Arora, 2003; Drewniak et al., 2013). No study has applied such a model at global scale to investigate joint impacts of environmental change and land management on associated changes in agricultural yields, water pollution and carbon balance.

The production of food and the protection of the environment often require conflicting strategies. Compared to forests, agricultural lands have lower carbon sequestration rates and enhanced nitrogen leaching, and agricultural production is hence done at the expense of other ecosystem services that those lands might otherwise provide; inten-

ESDD
6, 1047–1100, 2015

Soil C management, large-scale Earth system modelling

S. Olin et al.

sifying agricultural production might have further detrimental effects on these ecosystems (Tilman et al., 2002). At the same time, the world's population needs to be fed, and a more nitrogen-intensive agricultural system with higher productivity may result in a lower overall area in use for agriculture, leaving aside a greater area that can be devoted to the provision of other ecosystem services. This debate, often termed land-sparing vs. land-sharing, is currently a matter of great scientific and political debate (Phalan et al., 2011). These trade-offs between agricultural production on the one hand and carbon sequestration and reduction of nitrogen leaching on the other have given rise to a number of mitigation strategies in agricultural practice that have only a limited impact on production but contribute to other ecosystem services.

From an ecosystem carbon-pool-size perspective, the largest effect on terrestrial carbon storage through agricultural management practices is in fact induced through harvest (Smith et al., 2012; Pugh et al., 2015), as this removes a considerable amount of biomass each year from the ecosystem. Harvest is, however, the fundamental purpose of croplands and pastures, and is rarely discussed as an element of a management strategy targeting enhanced environmental value. Management practices need to move into focus in global-scale modeling, and some of the key interventions are reviewed below. One management option related to harvest is residue-removal after harvest (Lal and Bruce, 1999). Removing residues for use in bio-fuel production is an appealing measure, as making multiple use of the existing croplands may be seen as a win-win situation (Lal, 2004b; Smith et al., 2012). However, not incorporating residues into soils results in their becoming drained of soil organic carbon (SOC); which retains water and nutrients and thus affects the soil fertility (Lal, 2004b; Smith et al., 2012). Another practice that is often debated is tillage (Lal, 2004a, 2008). Different forms of tillage have been used for centuries to promote the release of nutrients from the soil organic matter (SOM) for uptake by crops. However, the aeration of the soil associated with the mechanical disturbance of the soil profile increases heterotrophic respiration (R_h), and thus enhances soil C losses to the atmosphere (Chatskikh et al., 2009; Lal, 2004a). No-till management has gained popularity as a potential climate change mit-

ESDD
6, 1047–1100, 2015

igation measure, as it can prevent management-related losses of soil C stocks (Lal, 2004a). But while no-till is expected to favour carbon retention by agricultural fields, the strength and persistence of any sink is debated (Lal, 2004a; Schlesinger, 2000). In a review on soil C sequestration, comparing conventional and no-till, Baker et al. (2007) found that the top soil in no-till treatments did contain more C, but the C density below the top soil layer in the conventionally tilled fields was higher, and there was no significant difference in overall C densities between the two treatments. Moreover, the conversion of N to plant-available forms is reduced in untilled soils and can thus lead to lower crop productivity, which could in the long run decrease the soil's ability to store water and nutrients because the reduced release is partly counterbalanced by a reduced input of new organic material (Lal, 2004a).

Timing of farmer practices such as sowing and harvest, fertilisation or irrigation are crucial for calculation of yields and – from the fertilisation perspective in particular – N leaching, but these practices are unlikely to affect carbon cycling on a global scale (Pugh et al., 2015). A major challenge is therefore to identify practices that increase soil C sequestration while maintaining or increasing current yields and at the same time without detrimental side-effects on ecosystems.

In this study we employ the land-use enabled version of a global DVM, LPJ-GUESS (Lindeskog et al., 2013; Olin et al., 2015), to explore and quantify the effectuality of alternative management strategies targeting mitigation of the negative effects of agriculture on carbon and nitrogen cycles. To this end, we extended the model to include N dynamics for crops, and the response of different N-application rates was evaluated on local to regional scale. Management options considered are tillage, cover-crops and manure application. We quantify management effects on soil carbon pools, yields and nitrogen losses through leaching from croplands and evaluate the model globally and for a representative range of climatic regions. In addition, the persistence and direction of these effects under future climate change scenarios are explored.

2 Materials and methods

2.1 LPJ-GUESS

LPJ-GUESS (Smith et al., 2014) is a DVM that simulates dynamic vegetation response to climate, atmospheric CO_2 levels ([CO_2]) and N input through competition for light, N, and water on a daily time step. Vegetation is represented by plant functional types (PFTs) that differ in their growth form, phenology, life-history strategy, distributional temperature limits and N requirements. C3 and C4 photosynthetic pathways are discriminated for grasses. Leaf-level net photosynthesis is calculated following a Farquhar-type approach, modified by Collatz et al. (1991, 1992) and scaled to the canopy following Haxeltine and Prentice (1996). Canopy conductance of water vapor and respiration of plant compartments other than leaves follows (Sitch et al., 2003). For potential natural vegetation, carbon allocation and stand dynamics, based on competition among age-classes of trees co-occurring in a number (here 5) of replicated patches in each grid cell, are modelled on a yearly time-step (Smith et al., 2001; Hickler et al., 2004). Disturbance by wildfire and other events such as storms are accounted for. Details of the representation of soil and plant physiological and growth processes are provided in Smith et al. (2001, 2014); Olin et al. (2015).

Soil C–N dynamics in LPJ-GUESS are based on the CENTURY model (Parton et al., 1993) in which SOM and litter are represented by 11 pools that differ in their C to N ratios (C : N), which are dynamic within prescribed limits (Smith et al., 2014). Mobilisation of mineral N is the result of heterotrophic decay and respiration which depends on the C : N and decay rates (K_d) of the SOM pools. Values of K_d are dynamic and vary between these pools, and are also modified by factors related to temperature and water content of the soil (Smith et al., 2014). Immobilisation of mineral N occurs when the C : N ratio of transferred SOM is larger than that of the receiving pool. Both organic and mineral N leaching are represented in the model and are related to percolation; for organic leaching there is also a dependency on soil silt and clay fractions.

ESDD
6, 1047–1100, 2015

The present study uses the managed land version of the model (Lindeskog et al., 2013; Olin et al., 2015). Crops are represented in the model by crop functional types (CFTs), which differ in their temperature requirements for survival, heat requirements for growth and their C allocation patterns. Land-use and land-cover change are modelled on a yearly basis (Lindeskog et al., 2013) based on the externally supplied fractional area change within a grid-cell. Sowing dates are determined dynamically in the model based on the prevailing climate in the grid cell (Lindeskog et al., 2013; Waha et al., 2011), and crops are harvested when specified heat sum requirements are fulfilled. The crops are allowed to adapt to the local conditions by adjusting the heat sum requirements to the historic climate (Lindeskog et al., 2013), reflecting a difference in varieties of a given crop grown in different climatic zones.

The allocation of C and N for the CFTs in the C-N version of LPJ-GUESS (Olin et al., 2015) is done on a daily time-step. C allocation depends on the plant's development stage which in turn is based on temperature and day length, and follows Penning de Vries et al. (1989), as described in detail for winter and spring wheat in Olin et al. (2015), and for maize in Table A1. N requirements for the plant vary during the growing period. This is reflected in the model by applying fertilisers proportionally at different developmental stages; see Appendix for more information on the timing of N fertiliser application for different CFTs.

At present, the C-N version of LPJ-GUESS is limited to three CFTs that are based on wheat and maize growth characteristics: a C3 crop with dynamic selection between spring and autumn sowing (presented here as winter wheat, WW), a C3 crop with sowing enforced in spring (spring wheat, SW) and a C4 crop (maize, MA). Allocation for SW and WW is described in Olin et al. (2015), MA-specific allocation parameters are listed in Tables A1–A2. For comparison with yield data, we adopt these three types to represent the entire spectrum of crops grown globally. In particular, wheat and rapeseed that have spring and autumn sown varieties were simulated as WW, whereas other C3 crops (beans, rice, tubers, etc.) were modelled as SW, since these are typically spring sown. Sorghum and millet were modelled as MA.

ESDD
6, 1047–1100, 2015

LPJ-GUESS has been evaluated against a range of experimental and observational data types, e.g. CO_2-fertilisation experiments (Olin et al., 2015; Smith et al., 2014), ecosystem dynamics (Smith et al., 2014), vegetation seasonality (Lindeskog et al., 2013) and C fluxes at various scales (Ahlström et al., 2012; Piao et al., 2013; Wramneby et al., 2008). In Olin et al. (2015), the growth response to N fertiliser application on site scale (under ambient and elevated CO_2) and over a larger region (western Europe) was evaluated.

2.1.1 Cropland management

The cropland management options implemented in LPJ-GUESS are sowing, irrigation, tillage, N-application, cover crops and residue management. The latter four options are relevant for this study and will be described below.

Tillage

Tillage is implemented using a tillage factor (f_T) which affects K_d for selected SOM pools on croplands. Two tillage routines were implemented: moderate tillage where f_T affects the surface microbial pool and humus, and the microbial and slow turnover pool of the soil; and full tillage in which K_d for the metabolic and structural surface pools and the passive and metabolic pools of the soil are also affected. The two tillage levels are not intended to represent different tillage practices, but rather to span uncertainties in the overall effect of tillage on soil respiration rates. The value of f_T (1.94) is taken from Chatskikh et al. (2009), and modifies K_d ($K'_d = f_T K_d$) throughout the year.

N application

Fertilisers are applied as mineral N (Olin et al., 2015). The timing of fertiliser applications in the model roughly coincides with the crucial developmental periods of plants being applied at the development stages (DS) 0, 0.5 and 0.9 (Olin et al., 2015) in CFT-specific amounts listed in Table A2.

ESDD
6, 1047–1100, 2015

Here we have extended the available N fertiliser application management options to also include manure application in the first of the three events (DS = 0, sowing). The manure is derived from the mineral N application and is applied as an increase in the metabolic and structural SOM pools with a C : N of 30, which has been chosen to represent the C and N content in manure from sources ranging from poultry waste (C : N ~ 15) to straw-rich manure from livestock (C : N $\gtrsim$ 40), (Nieder and Benbi, 2008). As the metabolic and structural SOM pools have different turnover (decomposition) rates the manure-derived N becomes available for an extended period in the soil.

Cover crops

Cover crops are intermediate crops that are grown in-between the main agricultural growing seasons. This can occur either as a fallow that stretches over the subsequent growing season or within a year (Follett, 2001). A common practice is to sow N-fixing plants such as legumes as cover crops, but grasses are also used. If the cover crop is not harvested but, for example, ploughed in, some of the captured or retained nutrients, as well as the carbon content of the crop biomass, are retained in the soil, enhancing nutrient availability.

In our implementation, cover crops are grown in-between two growing periods of the generic main crop used if the crop-free period is longer than 15 days. At the time of sowing of the subsequent main crop, the cover crop biomass is added to the soil litter pool. C and N allocation of the cover crop is done daily, with a leaf-to-root ratio that depends on the plant water status. In case of water stress, a functional balance response is introduced and allocation to roots increases relative to leaves. Cover crops are modelled as grasses, being "planted" with an initial C mass of 0.01 kg C m^{-2} and N mass that is based on the C : N_{min} value for grasses (C : N_{min} = 16). Symbiotic N-fixation, such as in legumes – common as cover crops in temperate latitudes – is not yet implemented.

Residue removal

A measure to increase the soil fertility and decrease the water loss, in particular in arid areas, is to leave the residues on the ground after harvest (Lal, 2004a; Smith et al., 2012). This practice is represented in our model by removing only a fraction (default set to 75 %) of the biomass remaining following harvest, thus leaving the rest as litter which enters the normal soil-decomposition calculations.

2.2 Experimental setups

Our study is divided into two parts. In the first part we test the ability of LPJ-GUESS to simulate present-day soil C and yield response to management by comparing simulated results with datasets of soil C in crop fields, potential C sequestration after a change in management, and global yield statistics. In the second part of the study, we investigate the effectuality of alternative crop management options described in Sect. 2.1.1 for mitigating climate change through increased carbon retention in cropland soils. The sensitivity of soil carbon sequestration to these management options is first studied for present-day climate conditions, assessing relative effects in different regions. Subsequently, we force the model with General Circulation Model (GCM)-simulated climate under a 21st century future climate projection to investigate combined effects of future changes in multiple ecosystem drivers on cropland ecosystem carbon balance.

For simulation over the recent historic period (1901–2006), gridded monthly mean observations from CRU (precipitation, air temperature and cloudiness, Mitchell and Jones, 2005) were used. For the future climate simulations, monthly climate data were adopted from four GCMs (CCSM4, Gent et al., 2011; MPI-ESM-LR, e.g. Stevens et al., 2013; IPSL-CM5A-LR, Dufresne et al., 2013; and HadGEM2-ES, Collins et al., 2011) from the CMIP5 data set (Taylor et al., 2011) and were bias corrected against CRU for monthly means over the period from 1961–1990, as described in (Ahlström et al., 2013). Climate data for the contrasting RCPs 2.6 and 8.5 radiative forcing projections

ESDD
6, 1047–1100, 2015

(Moss et al., 2010) were selected based on the availability of projections of future N-fertilisation.

For all simulations soil C and N pools were initialised using a 500 year "spin-up" using atmospheric [CO_2] from the first historic year (1901 for the historical CRU-based simulations and 1850 for the CMIP5 simulations) combined with repeatedly cycled, detrended climate input using the first 30 years of the historic climate data set. For comparison with the CRU simulations described above, the spin-up in the CMIP5 simulations was set to 450 years, followed by a simulation for years 1850–1901 with dynamic climate but constant [CO_2] (using the [CO_2] for 1901).

N atmospheric deposition was provided as decadally-varying monthly averages from the ACCMIP data set (Lamarque et al., 2010) transformed to the resolution of the climate data following (Smith et al., 2014; Wårlind et al., 2014).

As N-fertiliser input for the croplands, data from (Zaehle et al., 2010a) were used for the historical time period starting from 1901 (CRU) and 1850 (CMIP5); for the future period (2006–2100), a dataset described in Stocker et al. (2013) was used, which expands on the data set from Zaehle et al. (2010a), and includes simulated future fertiliser applications from integrated assessment models (RCP 2.6, Bouwman et al., 2013; RCP 8.5 Riahi et al., 2011). In addition, a simulation using N-fertiliser information from AgGRID (Elliott et al., 2014) was performed for the comparison of yields with national statistics from the FAO. The AgGRID dataset provides a long-term mean N fertiliser input for each grid cell representing present day (approximately the year 2000). In these simulations the input from (Zaehle et al., 2010a) was used until 1990, subsequently switching over to AgGRID data.

Land cover information was adopted from (Hurtt et al., 2011), with the forested, rangeland and urban classes treated as natural land cover. During spin-up, cropland fraction was linearly increased from an assumed baseline of zero at 1750 to the first historic value (1901 for CRU and 1850 for CMIP5). The number of years for this transition (150 years for the CRU-based and 100 years for the CMIP5 simulations) was chosen to ensure that the soil C and N pools of the natural vegetation fraction of each grid cell reached steady-state by the end of the spin-up. While this procedure will likely result in higher SOM pools in areas such as central Europe, India and the Middle East where agriculture has been present for many centuries, it will be most realistic for regions where most agricultural expansion has taken place over the last 100–200 years. Grid cell fractions of crop coverage for those grid cells where data on crop species exist were taken from MIRCA (Portmann et al., 2010), and aggregated to the three CFTs as described in Sect. 2.1. The relative CFT cover fractions were conserved over time, and information from the neighbouring cells was used using a distance weighted mean for grid cells that lack information in the MIRCA data set.

As soil input, fractions of clay, silt and sand from the WISE 3.0 dataset (Batjes, 2005) were used. Hydrological properties of the soil were calculated following Eqs. (19)–(20) from Olin et al. (2015).

2.2.1 Soil carbon and management response

Soil columns from croplands in the WISE 3.0 data set (Batjes, 2005) were used to evaluate the ability of LPJ-GUESS to model cropland soil C. Soil carbon from the top 1.5 m was averaged for each 0.5° grid cell (≈ 1000). As no detailed information was available on the management or land-use history for the different soil column sites the CFT fractions from (Portmann et al., 2010) were used together with N-fertiliser input as described above.

In (Stockmann et al., 2013), data on long term soil carbon response to the management options (cover-crops, no-tillage and manure application) were divided between four climatic regions: humid temperate, dry temperate, humid tropical and dry tropical. In order to compare our simulated carbon sequestration with the findings of (Stockmann et al., 2013), each simulated grid cell with soil data was classified to be either tropical (24° S > latitude < 24° N) or temperate (24° S < latitude > 24° N and latitude < 60° N), as depicted in Fig. B2. These categories were further subdivided into dry if the water balance coefficient (WBC = precipitation – potential evapotranspiration) was negative, and humid if positive. Each of the resulting four classes covered approximately 200 grid cells, evenly spread over the continents (Fig. B2). Some 200 of the grid cells were either in the boreal zone or not included in the climate dataset. Management practices were enabled from year 1990 and throughout the remaining simulation period. For the simulations using CRU climate input, the last 30 years of climate and [CO_2] (381 ppm), N deposition and fertiliser from the last year, were repeated until 2100, the end of the CMIP5 climate data set, in order to allow soil carbon and nitrogen pools to reach a new equilibrium after the management shift.

2.2.2 Management, global soil C and N leaching

The effect of the different management strategies considered (no-tillage, manure application, cover-crops and leaving residues) on simulated global crop yields, soil C pool size, and N leaching were tested in a factorial experiment where managements was turned on at the beginning of the simulation. The simulated yields, soil C and N-leaching were then compared with a baseline simulation (F_{std}, Table 2.1.1) with settings as in (Lindeskog et al., 2013; Smith et al., 2014; Olin et al., 2015).

To be able to compare our results with previous estimates of global soil C and N pools and N leaching from LPJ-GUESS (Smith et al., 2014), a simulation with potential natural vegetation (PNV) was also conducted. In addition, an optimised simulation setup was created (F_{opt}), where the management from Table 1 that yielded the largest increase in soil carbon per grid cell was selected, for the CRU and CMIP5 simulations.

3 Results

3.1 Yield comparison

LPJ-GUESS wheat (C3) and maize (C4) yields were simulated using the gridded N-fertiliser dataset (Elliott et al., 2014) and compared to reported yields from FAO[1] for

[1] FAOSTAT, http://faostat3.fao.org/home/E

ESDD
6, 1047–1100, 2015

the years 1996–2005 (Fig. 1). The overall model agreement with reported wheat yields per country was good across all wheat producing countries, with a correlation coefficient of 0.73. Maize yields had a lower agreement (correlation coefficient 0.46), with simulated yields overestimating the observations for most countries that have a low maize production, (e.g., Mexico, China and many African countries; Fig. 1). However, with exception of China and Mexico, yields in high producing countries were captured well, including the largest producer, the USA.

The total simulated production (wet weight) of all agricultural crops (including cereals, tubers and pulses) of 2.7 Gt, was within 30 % of what is reported to the FAO, 3.5 Gt for the period 1996–2005 (cereals, 2.12; coarse grain, 0.93; roots & tubers, 0.28[2]; pulses, 0.06; oil crops, 0.11).

3.2 Simulated soil C and its response to management

Simulated soil C pools (0–1.5 m) for the selected grid cells (Sect. 2.2.1) were compared against data from soil cores from agricultural fields for the four climatic regions (Batjes, 2005). This comparison did not aim to reproduce observed C values at the individual field scale, as this would require to capture individual site meteorology as well as details on land-use history. Consequently, per-site comparison of simulated vs. observed soil C resulted in low correlations of 0.05–0.14, but the mean and spread over the climatic zones were captured by the model (Table 2).

In Fig. 2, the simulated mean soil C sequestration response to the three managements (no-till, manure and cover-crops) is compared to estimates of potential soil C sequestration from Stockmann et al. (2013) for the simulated climatic regions over the historic period (1990–2006). Besides the model's average regional response to the three management options, Fig. 2 illustrates how the soil C sequestration in response to the onset of management (here: in the year 1990, see Sect. 2.2.1) evolves over time. The simulated long term (100 years) mean soil C sequestration by using manure on tropical

[2]Corrected for moisture content, value from FAOSTAT, 0.68 Gt.

soils was ca. 0.001 $kg\,C\,m^{-2}\,yr^{-1}$, declining to negligible levels by the end of the simulated period. For no-till, the long term mean C sequestration was 0.003 $kg\,C\,m^{-2}\,yr^{-1}$ or higher for all treatments, and levelled off to ca. 0.002 $kg\,C\,m^{-2}\,yr^{-1}$ by simulation year 2100. The highest mean C sequestration rates were found for manure in the humid temperate climatic regions (0.006 $kg\,C\,m^{-2}\,yr^{-1}$) and for cover-crops in the tropical humid regions (0.008 $kg\,C\,m^{-2}\,yr^{-1}$), in both cases levelling off to below 0.001 $kg\,C\,m^{-2}\,yr^{-1}$ by the end of the simulation period.

3.3 Global responses to management

The simulated management options resulted in an increase in cropland soil C, for all climatic regions (Fig. 3), with the largest global increase, as expected, for the option in which the management that yielded the largest carbon sequestration in a given grid cell was chosen (F_{opt}). With the exception of no residue removal, the simulated management treatments reduced N leaching (expressed here as negative anomalies), with cover-crop resulting in the largest decline. Cover crops and no-residue removal had opposite effects on both yields and N leaching. The reduction in N leaching from cover crops (∼ 15 %) was accompanied by a decline in simulated global yields of 5 %. The large negative effect of cover crops on simulated yields in the temperate humid climatic region is due to the implicit competition over the available N between the cover crop and the main crop, the low temperature makes the decomposition of the SOM slow and in turn the release of N more evenly spread throughout the year. The N retained in the system is locked in SOM, and not easily available for plant uptake, the opposite happens in the tropical regions and especially so for the humid tropics, where turnover of the SOM is relatively fast due to the prevailing warm and moist conditions. Leaving all the residues on the fields (no residue removal) was the only treatment that increased the modelled yields both globally and for all climatic regions, but with the environmental "cost" of an increase in N-leaching. The increase in both modelled yields and N leaching is obtained because N becomes available for plant uptake and transport over

ESDD
6, 1047–1100, 2015

a longer period, and between the growing periods there is nothing growing that can take up the available nitrogen. In all treatments, the soil N pools were higher than for the standard simulation (Table 3), which is caused by the reduction in leaching and the incorporation of nitrogen in SOM.

In general, the soil C pools simulated with the managed land version of LPJ-GUESS were slightly larger than simulated with PNV (Table 3), which is due to higher C storage in pastures compared to the natural vegetation they have replaced (e.g. Central Asia and parts of the Great Plains of North America) and also in high-productivity croplands that receive high inputs of N fertilisers (e.g. Egypt and western China; results not shown here).

From the simulations of different cropland management options, the management combination that yielded the largest SOC stocks 1996–2005 was chosen for each grid cell (F_{opt}); the spatial patterns are shown in Fig. 4, F_{CC} and F_{NT} being the most dominant and with distinct differences with F_{CC} mostly in humid tropical areas and F_{NT} in subtropical and temperate regions.

Figure 5 depicts the evolution over time of the effects of implementing the different soil carbon sequestration managements for two future climate change, CO_2 and land-use change scenarios. The spread that can be seen around the simulations with CRU forcing in Fig. 5 originates from the GCM climate variability, which can be seen also during the historic period (Fig. B1b). In the scenarios of land-use change (Hurtt et al., 2011), there is a steady increase of cropland area globally, which is most extreme for RCP 2.6 (Fig. B1a). Differences between the RCP 2.6 and 8.5 cases regarding the effects of management are consistently seen only for cropland soil C storage, with values being higher for RCP8.5 compared to RCP 2.6. Manure and no-tillage did not affect calculated N leaching or yields under future conditions any more than for present-day forcing. The effect of cover crops and best carbon management for RCP 8.5 was an enhanced reduction of yields and enhanced N leaching compared to the standard model set-up.

ESDD
6, 1047–1100, 2015

For the future simulations, there were changes in the optimal C sequestration management (Table 4), most of these “transitions” (∼ 7 % for RCP 2.6 and ∼ 9 % for 8.5) being from no-till to the other managements options (Fig. 6).

4 Discussion

Olin et al. (2015) addressed the effect of N-fertiliser applications on crop yields in Europe. In the present study we extended this analysis to the global scale and address the effect of additional land-management practices, other than fertiliser applications, on crop yields and carbon retention in cropland ecosystems and soils. The management practices explored are widely-used approaches that have been recommended as suitable for climate change mitigation and claimed to have benefits for a range of ecosystem services.

4.1 Soil carbon and nitrogen

Large-scale models like LPJ-GUESS are not designed for making assessments of local management decisions, but are optimised to address consequences of management decisions across regions and on the global scale (Rounsevell et al., 2014). The accurate modelling of soil carbon pool sizes and changes is of great importance when assessing impacts of global environmental change, since soils are the main long-term terrestrial sink of carbon (Smith, 2004a). This has proven to be a difficult task to master for DVMs (McGuire et al., 2001; Sitch et al., 2008) and earth system models (Todd-Brown et al., 2013). One cause for such inaccuracy may be the limited availability of observational soil carbon data. Global estimates of soil carbon and nitrogen pools are derived by extrapolation of highly-variable point observations from soil inventories or from data-based modelling. For instance, global C and N densities reported by Batjes (2014) (see Table 3) were derived by extrapolating measurements taken in 4353 soil cores across all biomes, using maps of soil types and land cover. LPJ-GUESS projections of soil N pools agree well with other estimates, the soil C pools are at the low end of generally reported global estimates (Ciais et al., 2013; Stockmann et al., 2013), which can partially be attributed to absence of wetland and permafrost processes in the current model setup (Miller and Smith, 2012; Tarnocai et al., 2009; Wania et al., 2009).

When making projections on global C pools, the information on land-use history is vital (Pongratz et al., 2014). In our simulations, the assumption that the main – natural to cropland – conversions started at 1750, could have resulted in overestimations of C stored in agricultural soils. When focusing on site data collected for croplands and grouped by four climate regions (Table 2), simulated average C pools in LPJ-GUESS were higher than observations, especially for temperate soils. It is to be expected that many of these sites, especially in temperate environments, would have been under land use for very long periods, which could well lead to lower C pools compared to our modelling assumptions. Moreover, we do not have comprehensive information on present management practices, or how these would have changed over time. Still, the among-grid-cell variations in C pools were similarly large in observed and simulated data (Table 2), suggesting that the model response is sound overall.

4.1.1 Carbon sequestration potential through cropland management

Global-scale modelling of the impacts of specific land-management options is in its infancy, but since a number of future climate and socioeconomic scenarios highlight the importance of land-based mitigation, and because of the multiple trade-offs that exist with other ecosystem services, they are of importance for future research and practical applications. Published estimates of the global carbon sequestration potential on existing cropland due to different types of cropland management range between 0.34–0.57 $\mathrm{Pg\,C\,yr^{-1}}$ for present-day environmental conditions (Lal, 2004a). Our model estimate when implementing the best practice (from the perspective of maximising C storage) globally is roughly 20 % of that value. Figure 3 shows a global increase of ca. 5 % in soil C for the F_{opt} case (ranging from 4 to 9 % between large regions),

ESDD
6, 1047–1100, 2015

which equates to an annual uptake of 0.08 $\mathrm{Pg\,C\,yr^{-1}}$ globally compared to the standard model version. The exact reasons for these low simulated uptake rates are difficult to assess, but representing land-use history and land-management practices at a large regional to global scale is a recognised challenge. In the CLM model (Levis et al., 2014), a country-specific tillage management has been implemented, which is not constant over the year, but carried out in connection with harvest. The authors found that estimations of the land-use emissions with CLM without tillage practices underestimates the emissions caused by agricultural practices. For a global scale simulation, this underestimation was 0.4 $\mathrm{Pg\,C\,yr^{-1}}$. When comparing the results from Levis et al. (2014) to the simulation in our study corresponding to that ($F_{\mathrm{NT}} - F_{\mathrm{std}}$), our estimate is that the error from not including tillage in the simulations is some 0.02 $\mathrm{Pg\,C\,yr^{-1}}$. We have chosen to implement uniform management for tillage in this study, reasoning that the additional assumptions one would need to make to resolve spatially-varying tillage would increase the uncertainty in our model predictions, in particular because of the absence of available information on future tillage practices.

Another important aspect is productivity during growing season and the possibility for multi-cropping. In many tropical areas the growing season is not limited to a short period of the year, especially in the humid tropics where two or more crops may be grown in sequence (Francis, 1989). Currently LPJ-GUESS is restricted to one growing period per year for the primary crop. Multiple cropping has been implemented in other modelling frameworks, such as LPJmL (Waha et al., 2013). Multiple cropping does not always increase the yields of the economic crops, but results in a more resilient cropping system with more than one harvest per year and thus reduces the risk of complete crop failures, while promoting high net productivity (Francis, 1989), and is thus also relevant to consider from a carbon cycle perspective. Thus, the simplifications we necessarily have to include in a global model regarding some management applications might lead to overall lower C sequestration compared to other published estimates (Lal, 2004a; Smith, 2004b). However, it also needs to be noted that these previous estimates are based on empirical modelling, not accounting for process-level interactions between vegetation, soils and the abiotic environment. In a review of the potential for countries to fulfil emissions reduction obligations under the Kyoto protocol IPCC (1996); Schlesinger (2000) found only a small or even no potential for C sequestration in cropland soils, while (Powlson et al., 2014) argued that no-tillage over tillage enhances some important soil properties but has a small overall effect of total agricultural soil C.

4.2 Yields

Compared to other measures of global C flows, statistics on crop production and yields are relatively accessible, and encompass relatively long time-series, albeit with differing quality between individual countries. While yield is not a direct measure of the net primary productivity (NPP), it is a good proxy for trends and variability of carbon flows on croplands (Haberl et al., 2007) and thus relevant for the estimation of fluxes and pools on agricultural fields. From a food production perspective, Olin et al. (2015) showed that including C–N dynamics and fertiliser input significantly increased model performance compared to the C-only version of LPJ-GUESS (e.g. Rosenzweig et al., 2014) for yield modelling and responses of yields to environmental changes. This was expected, since the C-only version intentionally represents a situation not limited by nutrients. The data sets used in this study were either designed for crop modelling in the AgMIP project (Elliott et al., 2014), or for studying global flows of carbon and nitrogen (rather than yields) (Stocker et al., 2013; Zaehle et al., 2011). When using the former (Elliott et al., 2014), the model performance was significantly improved (an increase in model agreement with observed yields from (R^2) 0.25 to 0.53 for WW and from 0.1 to 0.25 for MA). However, since the AgMIP dataset lacks information on temporal variations and trends, it could not be applied to transient historical or future simulations of global yields, C and N flows. Previous studies with global models have simulated yields (e.g. PEGASUS Deryng et al., 2011, R^2 for WW = 0.22, MA = 0.39, and DayCent Stehfest et al., 2007 R^2 for WW = 0.66, MA = 0.67). Our results compare favourably with these studies for WW, but less so for MA. The C-N version of our model has not yet

ESDD
6, 1047–1100, 2015

been evaluated and parameterised against observations of maize yields, and the lower degree of agreement with data was expected.

4.3 N leaching

Global estimates of N leaching from terrestrial ecosystems are uncertain (Gruber and Galloway, 2008), and the estimates with LPJ-GUESS fall well within the broad range of published annual global totals (Table 3). Only a few other global studies with DVMs (e.g. Smith et al., 2014; Stocker et al., 2013; Yang et al., 2009; Zaehle et al., 2010b) have reported N leached from terrestrial ecosystems. For models that included N-fertiliser applications, we estimated a range from 63 $\mathrm{Tg\,N\,yr^{-1}}$ (Yang et al., 2009)[3] to 133 $\mathrm{Tg\,N\,yr^{-1}}$ (Stocker et al., 2013)[4]. None of these simulation studies accounted for croplands explicitly, non-harvested grasslands in Zaehle et al. (2010b) and harvested grasslands in Stocker et al. (2013) were used as proxies for croplands. Zaehle et al. (2010b), estimated the total N leached to aquatic ecosystems from terrestrial sources to be 86 $\mathrm{Tg\,N\,yr^{-1}}$, out of which 57 $\mathrm{Tg\,N\,yr^{-1}}$ was attributed to agricultural ecosystems. These estimates for the entire land surface are considerably larger than the estimates provided here (24–66 $\mathrm{Tg\,N\,yr^{-1}}$ for the simulations including croplands, Table 3). Among the simulations performed here, the simulation without residue removal (F_{NR}) was the only one in which N leached from croplands was of comparable magnitude to the findings of Zaehle et al. (2010b). In our study fertilisers are applied at specific crop developmental stages with amounts that match the CFT specific demand (see Table A2), whereas in Zaehle et al. (2010b) three applications with equal amounts were spread using climate indicators defining the peak in the growing season. This could lead to higher leaching when fertiliser application is not timed to coincide with the peak of the

[3]Derived by scaling their average 0.47 $\mathrm{g\,N\,m^{-2}\,yr^{-1}}$ by the ice-free land area of $1.33 \times 10^{14}\,\mathrm{m^2}$, consistent with the estimates done elsewhere in this study.

[4]derived from the N_2O emissions of 0.8 $\mathrm{Tg\,N\,yr^{-1}}$ stemming from N-leaching and the constant fraction of leached N that is emitted as N_2O, 0.6 % that is assumed in the study.

ESDD
6, 1047–1100, 2015
Soil C management, large-scale Earth system modelling
S. Olin et al.

growing season when crop N uptake is highest. Despite its importance for the overall amount of leached N (Cameron et al., 2013), timing of fertiliser applications alone cannot explain the difference between this study and Zaehle et al. (2010b). By contrast to the three other DVM studies mentioned above, LPJ-GUESS treats all inorganic N as one pool, as opposed to modelling nitrate and ammonium separately. A fraction of this pool is leached without any distinction of the nitrogen species, while in reality, most of the nitrogen leached is in the form of nitrate (Smil, 1999), and only a small amount is in the form of organic N or ammonium, the latter mainly in association with extreme events like floods. During the growing season when crops (and plants in general) are active, leaching may thus be expected to be overestimated by our model as nitrates are the primary nitrogen source for plants (Penning de Vries et al., 1989), while during the fallow periods with no or only very little vegetation cover – and consequently relatively higher abundance of nitrates as compared to ammonium – the nitrogen exported in conjunction with run-off and drainage will tend to be underestimated.

4.4 Trade-offs and win-win management options

Due to the rising human population, changing lifestyles, as well as a number of – sometimes conflicting – policies related to e.g., climate change mitigation, agriculture, conservation or water regulation, the demand for resources from land ecosystems is increasing, and also constantly changing. In order to achieve, ultimately, a sustainable use of natural resources there is a need to identify strategies that minimise degradation and wastage of resources while still addressing society's growing needs for land-based ecosystem services including agricultural production. To this end, information on the trade-offs implicit in different management strategies but also possible win-win situations is of high value. In our analysis we attempted to compare three important parameters related to ecosystem functioning (yield, C uptake and N leaching) in terms of how different forms of crop management may be expected to influence their relative patterns of change. From our results (Fig. 3), two general findings emerge. Firstly, none of the management options explored lead to a win-win situation in the sense of an in-

ESDD
6, 1047–1100, 2015

crease in all three of the examined variables. Secondly, general patterns of change on the global scale were – with some variability – also seen at the regional scale: we did (for present day conditions) not find a situation where a win-win at global scale was contingent upon trade-offs at large regional scale.

All the implemented management options targeting carbon benefits resulted in a net increase in simulated soil carbon (Fig. 3). Most of these also showed the added benefit of reduced leaching of N – albeit at the cost of reduced yields. Avoided residue removal stands out from this general pattern, resulting in increased soil C and increased yields, but at the same time enhanced N leaching. The largest effects, at least when taking the regional spread into consideration, were found when including cover crops as a management option. The relatively large reduction in yield found in the F_{CC} simulations resulted from indirect competition over water and nitrogen, which were not available for the new crops planted following the cover-crop period. Interestingly, even though the yields were substantially lower in F_{CC}, the total vegetation productivity was higher due to the extended growing period (not shown; global annual total NPP were $+0.25\,\mathrm{Pg\,C\,yr^{-1}}$ compared with F_{std}). This higher NPP was also reflected in the enhanced soil C content. In reality, cover crops are an often applied management technique to sequester or retain nutrients and carbon in the field, which is why legumes are a preferred choice. While LPJ-GUESS correctly simulates enhanced C sequestration with cover crops, symbiotic N-fixation is not yet implemented in the current crop version of the model. Hence, the indirect competition for N between cover crop and main crop discussed above may be overestimated in the model. Vegetation carbon and nitrogen turnover in the grass PFT used here for F_{CC} obviously is too slow to make nitrogen available for the following crops, in particular in the temperate regions, which could also underlie the strong simulated reduction in leaching.

Absence of residue removal was positive for soil carbon, as well as for yields, resulting from the higher litter input. Similar responses of enhanced C storage (up to 30 %) and increased yields (10–30 %) in response to residue management have also been

ESDD
6, 1047–1100, 2015

found for e.g. maize and soybean in the US (Wilhelm et al., 2004) and millet in Niger (Bationo et al., 1993).

Manure (F_{MN}) application had minor effects on any of the investigated processes, both globally and in any particular climatic region (Fig. 3). The relatively low effect on soil C might be caused by the relatively small fraction of the total N applied at sowing (which is the time when manure was also applied), 8 % for WW and 11 % for SW and MA. In terms of yield, the relatively high C : N (30), might have reduced crop productivity slightly, since the manure-N will not be available for plant uptake at sowing, but will be released from the SOM during the growing season. Still, in some of the high producing regions (e.g. north-western Europe and parts of China), manure application was the most effective management for carbon sequestration (Fig. 4); these are all areas where the N application rates in the data set used here are high (Zaehle et al., 2011), and thus the amount of carbon added to the soil is relatively large.

By contrast with moderate tillage, complete absence of tillage resulted in enhanced soil C, with only small to moderate yield reduction, and a small reduction of N loss through leaching. Depending on the regional climate and N-fertiliser applications, reductions in crop productivity by up to 0.5 t ha^{-1} were also reported for maize and winter wheat grown in the USA in a recent meta-analysis, comparing tillage to no-tillage (Ogle et al., 2012). A larger effect on C sequestration (at similarly small to moderate effects on yields) was only found when optimising for carbon sequestration also resulted in a moderate reduction in yields while achieving a reduction in the modelled N-leaching by ca. 30 % (Fig. 3). Considering the high global demand for food today and in the future, a 5 % yield reduction may be difficult to motivate in exchange for a 5 % increase in soil C and reduced leaching. Avoiding the loss of food production would require either further intensification (likely resulting in enhanced N losses through leaching) or expansion of crop and pasture areas (potentially interfering with other ecosystem services). In this regard, regional differences are crucial to consider. Large vegetation carbon stocks in tropical forest ecosystems motivate the protection of these systems, limiting the further expansion of managed land in these ecosystems. Given that tropical areas

ESDD
6, 1047–1100, 2015

tend also to have the largest yield gaps (Licker et al., 2010), a much better strategy in these regions is to invest in sustainable intensification of existing managed land.

The initial difference between F_{opt} and F_{CC} in Fig. 3, where F_{CC} had a positive effect on yields until mid 1960s, is due to the fact that in the model, the cover-crops are being sown with a finite initial carbon and nitrogen mass. This results in more available nitrogen in the fields with this management (basically a fertilisation via the seeds), despite the indirect competition for nitrogen between the cover-crop and the main crop which subsequently also results in a relatively larger nitrogen export through leaching. Cover-crops have been used to re-vitalise croplands, the results shown here implies that the model partly captures this, but the simulated indirect competition is too strong and further studies and model developments are needed to better represent cover-crop management. Also, as the cover-crop implementation does not include symbiotic N-fixation, the simulated reduction in yields with that management could very well have resulted in the opposite effect, but as was seen for N-leaching prior to 1960 and also for the no-residue removal, maybe also an increase in the relative N-leakage.

5 Conclusions

We have presented a global model analysis highlighting effects of alternative crop management strategies for a range of core ecosystem processes and the services derived from them, related to interactions of climate change and land use change.

Our large-scale approach based on the simplifying assumption of uniform management across regions does not faithfully represent actual conditions, but instead allows the influence of different management actions to be evaluated, and geographical difference to be highlighted.

Results demonstrate that effects of management on cropland can be beneficial for carbon and nutrient retention without risking (large) yield losses. Nevertheless, effects on soil carbon are small compared with extant stocks in natural and semi-natural ecosystem types and managed forests. While agricultural management can be tar-

ESDD
6, 1047–1100, 2015

geted towards sustainable goals, from a climate change or carbon sink perspective avoided deforestation or reforestation constitutes a far more effective overall strategy for maintaining and enhancing global carbon sinks. However, enhanced carbon storage in agricultural soils could also be seen as a surrogate for enhanced soil structure and reduced erosion having additional (non-climate) environmental benefits.

Appendix: Allocation

In Olin et al. (2015) relationships between allocation to leaves (g_L), stem (g_{St}), root (g_R) and grains (g_Y) based on the allocation model of Penning de Vries et al. (1989) were established using a logistic growth function, a Richards curve (Richards, 1959), (Eq. A1):

$$f_i = a + \frac{b-a}{1+e^{-c(\mathrm{DS}-d)}} \tag{A1}$$

where f_i is the daily allocation of assimilates to a plant organ relative to e.g. the shoot, a is the asymptote when DS $\rightarrow 0$, b is the upper asymptote when DS $\rightarrow \infty$, c the growth rate, and d is the DS of maximum growth.

The relative relationships of daily assimilate allocation to the organs described with Eq. (A1):

$$f_1 = \frac{g_R}{g_R + g_L + g_{St}}, f_2 = \frac{g_L}{g_L + g_{St}}, f_3 = \frac{g_Y}{g_R + g_L + g_{St} + g_Y} \tag{A2}$$

And combining the equations in Eq. (A2) yields:

$$\begin{aligned} g_R &= f_1(1-f_3) \\ g_L &= f_2(1-f_1)(1-f_3) \\ g_{St} &= (1-f_2)(1-f_1)(1-f_3) \\ g_Y &= f_3 \end{aligned} \tag{A3}$$

ESDD
6, 1047–1100, 2015

Soil C management, large-scale Earth system modelling

S. Olin et al.

See Olin et al. (2015) for more details on how these relationships were derived.

Acknowledgements. This study is a contribution to the Strong Research Environment Land-Use Today and Tomorrow funded by the Swedish Research Council FORMAS (Contract No. 211–2009-1682). A. Arneth and T. A. M. Pugh acknowledge support from the European Commission in the FP 7 projects OPERAS (grant no. 308393) and LUC4C (grant no. 603542). M. Lindeskog was funded by the Mistra Swedish Research Programme for Climate, Impacts and Adaptation. This study is a contribution to the Strategic Research Areas BECC and MERGE and to the Lund University Centre for Studies of Carbon Cycle and Climate Interactions (LUCCI).

References

Ahlström, A., Schurgers, G., Arneth, A., and Smith, B.: Robustness and uncertainty in terrestrial ecosystem carbon response to CMIP5 climate change projections, Environ. Res. Lett., 7, 044008, doi:10.1088/1748-9326/7/4/044008, 2012. 1056

Ahlström, A., Smith, B., Lindström, J., Rummukainen, M., and Uvo, C. B.: GCM characteristics explain the majority of uncertainty in projected 21st century terrestrial ecosystem carbon balance, Biogeosciences, 10, 1517–1528, doi:10.5194/bg-10-1517-2013, 2013. 1058

Arora, V. K.: Simulating energy and carbon fluxes over winter wheat using coupled land surface and terrestrial ecosystem models, Agr. Forest Meteorol., 118, 21–47, doi:10.1016/S0168-1923(03)00073-X, 2003. 1051

Baker, J. M., Ochsner, T. E., Venterea, R. T., and Griffis, T. J.: Tillage and soil carbon sequestration – what do we really know?, Agr. Ecosyst. Environ., 118, 1–5, doi:10.1016/j.agee.2006.05.014, 2007. 1053

Bationo, A., Christianson, C., and Klaij, M.: The effect of crop residue and fertilizer use on pearl millet yields in Niger, Fert. Res., 34, 251–258, doi:10.1007/BF00750571, 1993. 1072

Batjes, N. H. .: ISRICE-WISE global data ser of derived soil properties on a 0.5 by 0.5 degree grid (version 3.0), Report 08, ISRIC – World Soil Information, Wageningen, 2005. 1060, 1062, 1100

Batjes, N. H.: Total carbon and nitrogen in the soils of the world, Eur. J. Soil Sci., 65, 10–21, doi:10.1111/ejss.12114_2, 2014. 1065, 1088, 1089

Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., and Gerten, D.: Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Glob. Change Biol., 13, 679–706, doi:10.1111/j.1365-2486.2006.01305.x, 2007. 1051

Bouwman, L., Goldewijk, K. K., Van Der Hoek, K. W., Beusen, A. H. W., Van Vuuren, D. P., Willems, J., Rufino, M. C., and Stehfest, E.: Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period, P. Natl. Acad. Sci. USA, 110, 20882–20887, doi:10.1073/pnas.1012878108, 2013. 1059

Boyer, E. W., Howarth, R. W., Galloway, J. N., Dentener, F. J., Green, P. A., and Vörösmarty, C. J.: Riverine nitrogen export from the continents to the coasts, Global Biogeochem. Cy., 20, GB1S91, doi:10.1029/2005GB002537, 2006. 1089

Cameron, K., Di, H., and Moir, J.: Nitrogen losses from the soil/plant system: a review, Ann. Appl. Biol., 162, 145–173, doi:10.1111/aab.12014, 2013. 1050, 1070

Chatskikh, D., Hansen, S., Olesen, J. E., and Petersen, B. M.: A simplified modelling approach for quantifying tillage effects on soil carbon stocks, Eur. J. Soil Sci., 60, 924–934, doi:10.1111/J.1365-2389.2009.01185.x, 2009. 1052, 1056

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., et al.: Carbon and other biogeochemical cycles, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 465–570, 2013. 1050, 1051, 1066, 1089

Collatz, G., Ball, J., Grivet, C., and Berry, J. A.: Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer, Agr. Forest Meteorol., 54, 107–136, doi:10.1016/0168-1923(91)90002-8, 1991. 1054

Collatz, G., Ribas-Carbo, M., and Berry, J.: Coupled photosynthesis-stomatal conductance model for leaves of C_4 plants, Functional Plant Biol., 19, 519–538, available at: http://www.publish.csiro.au/paper/PP9920519, 1992. 1054

Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S.: Development and evaluation of an

ESDD
6, 1047–1100, 2015
Soil C management, large-scale Earth system modelling
S. Olin et al.

Earth-System model – HadGEM2, Geosci. Model Dev., 4, 1051–1075, doi:10.5194/gmd-4-1051-2011, 2011. 1058
Deryng, D., Sacks, W. J., Barford, C. C., and Ramankutty, N.: Simulating the effects of climate and agricultural management practices on global crop yield, Global Biogeochem. Cy., 25, 2, doi:10.1029/2009GB003765, 2011. 1068
Drewniak, B., Song, J., Prell, J., Kotamarthi, V. R., and Jacob, R.: Modeling agriculture in the Community Land Model, Geosci. Model Dev., 6, 495–515, doi:10.5194/gmd-6-495-2013, 2013. 1051
Dufresne, J.-L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., de Noblet, N., Duvel, J.-P., Ethé, C., Fairhead, L., Fichefet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J.-Y., Guez, L., Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, J., Joussaume, S., Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M.-P., Lefevre, F., Levy, C., Li, Z., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S., Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M., Swingedouw, D., Szopa, S., Talandier, C., Terray, P., Viovy, N., and Vuichard, N.: Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5, Clim. Dynam., 40, 2123–2165, doi:10.1007/s00382-012-1636-1, 2013. 1058
Eitelberg, D. A., van Vliet, J., and Verburg, P. H.: A review of global potentially available cropland estimates and their consequences for model-based assessments, Glob. Change Biol., 21, 1236–1248, doi:10.1111/gcb.12733, 2015. 1050
Elliott, J., Müller, C., Deryng, D., Chryssanthacopoulos, J., Boote, K. J., Büchner, M., Foster, I., Glotter, M., Heinke, J., Iizumi, T., Izaurralde, R. C., Mueller, N. D., Ray, D. K., Rosenzweig, C., Ruane, A. C., and Sheffield, J.: The Global Gridded Crop Model Intercomparison: data and modeling protocols for Phase 1 (v1.0), Geosci. Model Dev., 8, 261–277, doi:10.5194/gmd-8-261-2015, 2015. 1059, 1061, 1068
Evans, L.: Steps towards feeding the ten billion: a crop physiologists view, Plant Prod. Sci., 2, 3–9, 1999. 1050
FAO: The state of food and agriculture, available at: http://www.fao.org/docrep/011/i0100e/i0100e00.htm (last access: 9 June 2015), 2008. 1049
Follett, R.: Soil management concepts and carbon sequestration in cropland soils, Soil Till. Res., 61, 77–92, doi:10.1016/S0167-1987(01)00180-5, 2001. 1057

ESDD
6, 1047–1100, 2015

Francis, C. A.: Biological efficiencies in multiple-cropping systems, in: Advances in Agronomy, vol. 42, Adv Agron, doi:10.1016/S0065-2113(08)60522-2, 1–42, 1989. 1067

Galloway, J. N., Dentener, F. J., Capone, D. G., Boyer, E. W., Howarth, R. W., Seitzinger, S. P., Asner, G. P., Cleveland, C. C., Green, P. A., Holland, E. A., Karl, D. M., Michaels, A. F., Porter, J. H., Townsend, A. R., and Vörösmarty, C. J.: Nitrogen cycles: past, present, and future, Biogeochemistry, 70, 153–226, doi:10.1007/s10533-004-0370-0, 2004. 1050

Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., Lawrence, D. M., Neale, R. B., Rasch, P. J., Vertenstein, M., Worley, P. H., Yang, Z.-L., and Zhang, M.: The Community Climate System Model Version 4, J. Climate, 24, 4973–4991, doi:10.1175/2011JCLI4083.1, 2011. 1058

Gerland, P., Raftery, A. E., Ševčíková, H., Li, N., Gu, D., Spoorenberg, T., Alkema, L., Fosdick, B. K., Chunn, J., Lalic, N., Bay, G., Buettner, T., Heilig, G. K., and Wilmoth, J.: World population stabilization unlikely this century, Science, 346, 234–237, doi:10.1126/science.1257469, 2014. 1049

Grizetti, B.: Nitrogen as a Threat to European Water Quality, Cambridge University Press, Cambridge, UK and New York, NY, USA, doi:10.1017/CBO9780511976988.020, 2011. 1050

Gruber, N. and Galloway, J. N.: An Earth-system perspective of the global nitrogen cycle, Nature, 451, 293–296, doi:10.1038/nature06592, 2008. 1069, 1089

Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., and Fischer-Kowalski, M.: Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems, P. Natl. Acad. Sci. USA, 104, 12942–12947, doi:10.1073/pnas.0704243104, 2007. 1068

Haxeltine, A. and Prentice, I. C.: A general model for the light-use efficiency of primary production, Funct. Ecol., 10, 551–561, doi:10.2307/2390165, 1996. 1054

Hertel, T.: The challenges of sustainably feeding a growing planet, Food Security, 1–14, doi:10.1007/s12571-015-0440-2, 2015. 1049

Hickler, T., Smith, B., Sykes, M. T., Davis, M. B., Sugita, S., and Walker, K.: Using a generalized vegetation model to simulate vegetation dynamics in northeastern USA, Ecology, 85, 519–530, doi:10.1890/02-0344, 2004. 1054

Houghton, R. A., House, J. I., Pongratz, J., van der Werf, G. R., DeFries, R. S., Hansen, M. C., Le Quéré, C., and Ramankutty, N.: Carbon emissions from land use and land-cover change, Biogeosciences, 9, 5125–5142, doi:10.5194/bg-9-5125-2012, 2012. 1051

Hurtt, G., Chini, L., Frolking, S., Betts, R., Feddema, J., Fischer, G., Fisk, J., Hibbard, K., Houghton, R., Janetos, A., Jones, C., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D., and Wang, Y.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, Climatic Change, 109, 117–161, doi:10.1007/s10584-011-0153-2, 2011. 1059, 1064, 1090, 1099

IPCC: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Organization for Economic Cooperation and Development (OECD), Washington, DC, 1996. 1068

Lal, R.: Soil carbon sequestration to mitigate climate change, Geoderma, 123, 1–22, doi:10.1016/j.geoderma.2004.01.032, 2004a. 1052, 1053, 1058, 1066, 1067

Lal, R.: Carbon emission from farm operations, Environ. Int., 30, 981–990, doi:10.1016/j.envint.2004.03.005, 2004b. 1052

Lal, R.: Carbon sequestration, Philos. T. R. Soc. Lon. B, 363, 815–830, doi:10.1098/rstb.2007.2185, 2008. 1052

Lal, R. and Bruce, J.: The potential of world cropland soils to sequester C and mitigate the greenhouse effect, Environ. Sci. Policy, 2, 177–185, doi:10.1016/S1462-9011(99)00012-X, 1999. 1052

Lamarque, J.-F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P.: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, Atmos. Chem. Phys., 10, 7017–7039, doi:10.5194/acp-10-7017-2010, 2010. 1059

Le Quéré, C., Peters, G. P., Andres, R. J., Andrew, R. M., Boden, T. A., Ciais, P., Friedlingstein, P., Houghton, R. A., Marland, G., Moriarty, R., Sitch, S., Tans, P., Arneth, A., Arvanitis, A., Bakker, D. C. E., Bopp, L., Canadell, J. G., Chini, L. P., Doney, S. C., Harper, A., Harris, I., House, J. I., Jain, A. K., Jones, S. D., Kato, E., Keeling, R. F., Klein Goldewijk, K., Körtzinger, A., Koven, C., Lefèvre, N., Maignan, F., Omar, A., Ono, T., Park, G.-H., Pfeil, B., Poulter, B., Raupach, M. R., Regnier, P., Rödenbeck, C., Saito, S., Schwinger, J., Segschneider, J., Stocker, B. D., Takahashi, T., Tilbrook, B., van Heuven, S., Viovy, N., Wanninkhof, R., Wiltshire, A., and Zaehle, S.: Global carbon budget 2013, Earth Syst. Sci. Data, 6, 235–263, doi:10.5194/essd-6-235-2014, 2014. 1051

ESDD
6, 1047–1100, 2015
Soil C management, large-scale Earth system modelling
S. Olin et al.

Le Quéré, C., Moriarty, R., Andrew, R. M., Peters, G. P., Ciais, P., Friedlingstein, P., Jones, S. D., Sitch, S., Tans, P., Arneth, A., Boden, T. A., Bopp, L., Bozec, Y., Canadell, J. G., Chini, L. P., Chevallier, F., Cosca, C. E., Harris, I., Hoppema, M., Houghton, R. A., House, J. I., Jain, A. K., Johannessen, T., Kato, E., Keeling, R. F., Kitidis, V., Klein Goldewijk, K., Koven, C., Landa, C. S., Landschützer, P., Lenton, A., Lima, I. D., Marland, G., Mathis, J. T., Metzl, N., Nojiri, Y., Olsen, A., Ono, T., Peng, S., Peters, W., Pfeil, B., Poulter, B., Raupach, M. R., Regnier, P., Rödenbeck, C., Saito, S., Salisbury, J. E., Schuster, U., Schwinger, J., Séférian, R., Segschneider, J., Steinhoff, T., Stocker, B. D., Sutton, A. J., Takahashi, T., Tilbrook, B., van der Werf, G. R., Viovy, N., Wang, Y.-P., Wanninkhof, R., Wiltshire, A., and Zeng, N.: Global carbon budget 2014, Earth Syst. Sci. Data, 7, 47–85, doi:10.5194/essd-7-47-2015, 2015. 1051

Levis, S., Hartman, M. D., and Bonan, G. B.: The Community Land Model underestimates land-use CO_2 emissions by neglecting soil disturbance from cultivation, Geosci. Model Dev., 7, 613–620, doi:10.5194/gmd-7-613-2014, 2014. 1051, 1067

Licker, R., Johnston, M., Foley, J. A., Barford, C., Kucharik, C. J., Monfreda, C., and Ramankutty, N.: Mind the gap: how do climate and agricultural management explain the "yield gap" of croplands around the world?, Global Ecol. Biogeogr., 19, 769–782, doi:10.1111/j.1466-8238.2010.00563.x, 2010. 1050, 1073

Lindeskog, M., Arneth, A., Bondeau, A., Waha, K., Seaquist, J., Olin, S., and Smith, B.: Implications of accounting for land use in simulations of ecosystem carbon cycling in Africa, Earth Syst. Dynam., 4, 385–407, doi:10.5194/esd-4-385-2013, 2013. 1051, 1053, 1055, 1056, 1061

Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A. J. B., and Yang, H.: A high-resolution assessment on global nitrogen flows in cropland, P. Natl. Acad. Sci. USA, 107, 8035–8040, doi:10.1073/pnas.0913658107, 2010. 1089

McGuire, A. D., Sitch, S., Clein, J. S., Dargaville, R., Esser, G., Foley, J., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D. W., Meier, R. A., Melillo, J. M., Moore, B., Prentice, I. C., Ramankutty, N., Reichenau, T., Schloss, A., Tian, H., Williams, L. J., and Wittenberg, U.: Carbon balance of the terrestrial biosphere in the Twentieth Century: Analyses of CO2, climate and land use effects with four process-based ecosystem models, Global Biogeochem. Cy., 15, 183–206, doi:10.1029/2000GB001298, 2001. 1065

Miller, P. A. and Smith, B.: Modelling tundra vegetation response to recent arctic warming, Ambio, 41, 281–291, doi:10.1007/s13280-012-0306-1, 2012. 1066

Mitchell, T. D. and Jones, P. D.: An improved method of constructing a database of monthly climate observations and associated high-resolution grids, Int. J. Climatol., 25, 693–712, doi:10.1002/joc.1181, 2005. 1058
Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747–756, doi:10.1038/nature08823, 2010. 1059
Mueller, N. D., West, P. C., Gerber, J. S., MacDonald, G. K., Polasky, S., and Foley, J. A.: A tradeoff frontier for global nitrogen use and cereal production, Environ. Res. Lett., 9, 054002, doi:10.1088/1748-9326/9/5/054002, 2014. 1050
Nieder, R. and Benbi, D. K.: Carbon and Nitrogen in the Terrestrial Environment, Springer Science and Business Media, the Netherlands, 2008. 1057
Ogle, S. M., Swan, A., and Paustian, K.: No-till management impacts on crop productivity, carbon input and soil carbon sequestration, Agr. Ecosyst. Environ., 149, 37–49, doi:10.1016/j.agee.2011.12.010, 2012. 1072
Olin, S., Schurgers, G., Lindeskog, M., Wårlind, D., Smith, B., Bodin, P., Holmér, J., and Arneth, A.: Modelling the response of yields and tissue C : N to changes in atmospheric CO_2 and N management in the main wheat regions of western Europe, Biogeosciences, 12, 2489–2515, doi:10.5194/bg-12-2489-2015, 2015. 1053, 1054, 1055, 1056, 1060, 1061, 1065, 1068, 1074, 1075, 1092
Park, S., Croteau, P., Boering, K. A., Etheridge, D. M., Ferretti, D., Fraser, P. J., Kim, K.-R., Krummel, P. B., Langenfelds, R. L., van Ommen, T. D., Steele, L. P., and Trudinger, C. M.: Trends and seasonal cycles in the isotopic composition of nitrous oxide since 1940, Nat. Geosci., 5, 261–265, doi:10.1038/ngeo1421, 2012. 1050
Parton, W. J., Scurlock, J. M. O., Ojima, D. S., Gilmanov, T. G., Scholes, R. J., Schimel, D. S., Kirchner, T., Menaut, J.-C., Seastedt, T., Garcia Moya, E., Kamnalrut, A., and Kinyamario, J. I.: Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide, Global Biogeochem. Cy., 7, 785–809, doi:10.1029/93GB02042, 1993. 1054
Penning de Vries, F. W. T., Jansen, D. M., Berge, H. F. M., and Bakema, A.: Simulation of Ecophysiological Processes of Growth in Several Annual Crops, Centre for Agricultural Publishing and Documentation, Wageningen, the Netherlands, 1989. 1055, 1070, 1074

ESDD
6, 1047–1100, 2015

Phalan, B., Onial, M., Balmford, A., and Green, R. E.: Reconciling food production and biodiversity conservation: land sharing and land sparing compared, Science, 333, 1289–1291, doi:10.1126/science.1208742, 2011. 1052

Piao, S., Sitch, S., Ciais, P., Friedlingstein, P., Peylin, P., Wang, X., Ahlström, A., Anav, A., Canadell, J. G., Cong, N., Huntingford, C., Jung, M., Levis, S., Levy, P. E., Li, J., Lin, X., Lomas, M. R., Lu, M., Luo, Y., Ma, Y., Myneni, R. B., Poulter, B., Sun, Z., Wang, T., Viovy, N., Zaehle, S., and Zeng, N.: Evaluation of terrestrial carbon cycle models for their response to climate variability and to CO_2 trends, Glob. Change Biol., 19, 2117–2132, doi:10.1111/gcb.12187, 2013. 1056

Pongratz, J., Reick, C. H., Houghton, R. A., and House, J. I.: Terminology as a key uncertainty in net land use and land cover change carbon flux estimates, Earth Syst. Dynam., 5, 177–195, doi:10.5194/esd-5-177-2014, 2014. 1066

Portmann, F. T., Siebert, S., and Döll, P.: MIRCA2000–Global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling, Global Biogeochem. Cy., 24, GB1011, doi:10.1029/2008GB003435, 2010. 1060

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A., and Cassman, K. G.: Limited potential of no-till agriculture for climate change mitigation, Nature Climate Change, 4, 678–683, doi:10.1038/nclimate2292, 2014. 1068

Pugh, T. A. M., Olin, S., G., S., Lindeskog, M., and Arneth, A.: Carbon emissions from land-use change is substantially enhanced by agricultural management, Nature Climate Change, submitted, 2015. 1051, 1052, 1053

Ramankutty, N., Evan, A. T., Monfreda, C., and Foley, J. A.: Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000, Global Biogeochem. Cy., 22, GB1003, doi:10.1029/2007GB002952, 2008. 1050

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., and Rafaj, P.: RCP 8.5 – a scenario of comparatively high greenhouse gas emissions, Climatic Change, 109, 33–57, doi:10.1007/s10584-011-0149-y, 2011. 1059

Richards, F. J.: A flexible growth function for empirical use, J. Exp. Bot., 10, 290–301, doi:10.1093/jxb/10.2.290, 1959. 1074

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., and Foley, J. A.: A safe operating space for humanity, Nature, 461, 472–475, doi:10.1038/461472a, 2009. 1050

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., Boote, K. J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T. A. M., Schmid, E., Stehfest, E., Yang, H., and Jones, J. W.: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison, P. Natl. Acad. Sci. USA, 111, 3268–3273, doi:10.1073/pnas.1222463110, 2014. 1068

Rounsevell, M. D. A., Arneth, A., Alexander, P., Brown, D. G., de Noblet-Ducoudré, N., Ellis, E., Finnigan, J., Galvin, K., Grigg, N., Harman, I., Lennox, J., Magliocca, N., Parker, D., O'Neill, B. C., Verburg, P. H., and Young, O.: Towards decision-based global land use models for improved understanding of the Earth system, Earth Syst. Dynam., 5, 117–137, doi:10.5194/esd-5-117-2014, 2014. 1065

Schlesinger, W. H.: Carbon sequestration in soils: some cautions amidst optimism, Agr. Ecosyst. Environ., 82, 121–127, doi:10.1016/S0167-8809(00)00221-8, 2000. 1053, 1068

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Glob. Change Biol., 9, 161–185, doi:10.1046/j.1365-2486.2003.00569.x, 2003. 1054

Sitch, S., Huntingford, C., Gedney, N., Levy, P., Lomas, M., Piao, S., Betts, R., Ciais, P., Cox, P., Friedlingstein, P., Jones, C., Prentice, I., and Woodward, F.: Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs), Glob. Change Biol., 14, 2015–2039, 2008. 1065

Smil, V.: Nitrogen in crop production: an account of global flows, Global Biogeochem. Cy., 13, 647–662, doi:10.1029/1999GB900015, 1999. 1070, 1089

Smith, B., Prentice, I. C., and Sykes, M. T.: Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space, Global Ecol. Biogeogr., 10, 621–637, 2001. 1054

Smith, B., Wårlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J., and Zaehle, S.: Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model, Biogeosciences, 11, 2027–2054, doi:10.5194/bg-11-2027-2014, 2014. 1051, 1054, 1056, 1059, 1061, 1069

Smith, P.: Soils as carbon sinks: the global context, Soil Use Manage., 20, 212–218, doi:10.1111/j.1475-2743.2004.tb00361.x, 2004a. 1065

ESDD

6, 1047–1100, 2015

Soil C management, large-scale Earth system modelling

S. Olin et al.

Smith, P.: Carbon sequestration in croplands: the potential in Europe and the global context, Eur. J. Agron., 20, 229–236, doi:10.1016/j.eja.2003.08.002, 2004b. 1067
Smith, W., Grant, B., Campbell, C., McConkey, B., Desjardins, R., Kröbel, R., and Malhi, S.: Crop residue removal effects on soil carbon: measured and inter-model comparisons, Agr. Ecosyst. Environ., 161, 27–38, doi:10.1016/j.agee.2012.07.024, 2012. 1052, 1058
Spano, G., Di Fonzo, N., Perrotta, C., Platani, C., Ronga, G., Lawlor, D. W., Napier, J. A., and Shewry, P. R.: Physiological characterization of "stay green" mutants in durum wheat, J. Exp. Bot., 54, 1415–1420, doi:10.1093/jxb/erg150, 2003. 1050
Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., and Ludwig, C.: The trajectory of the anthropocene: the great acceleration, Anthrop. Rev., 2, 81–98, doi:10.1177/2053019614564785, 2015. 1049
Stehfest, E., Heistermann, M., Priess, J. A., Ojima, D. S., and Alcamo, J.: Simulation of global crop production with the ecosystem model DayCent, Ecol. Model., 209, 203–219, doi:10.1016/j.ecolmodel.2007.06.028, 2007. 1068
Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., Salzmann, M., Schmidt, H., Bader, J., Block, K., Brokopf, R., Fast, I., Kinne, S., Kornblueh, L., Lohmann, U., Pincus, R., Reichler, T., and Roeckner, E.: Atmospheric component of the MPI-M Earth System Model: ECHAM6, J. Adv. Modeling Earth Syst., 5, 146–172, doi:10.1002/jame.20015, 2013. 1058
Stocker, B. D., Roth, R., Joos, F., Spahni, R., Steinacher, M., Zaehle, S., Bouwman, L., Xu-Ri, and Prentice, I. C.: Multiple greenhouse-gas feedbacks from the land biosphere under future climate change scenarios, Nature Clim. Change, 3, 666–672, doi:10.1038/nclimate1864, 2013. 1059, 1068, 1069, 1099
Stockmann, U., Adams, M., Crawford, J., Field, D., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A., Courcelles, V., Singh, K., Wheeler, I., Abbott, L., Angers, D., Baldock, J., Bird, M., Brookes, P., Chenu, C., Jastrow, J., Lal, R., Lehmann, J., O'Donnell, A., Parton, W., Whitehead, D., and Zimmermann, M.: The knowns, known unknowns and unknowns of sequestration of soil organic carbon, Agr. Ecosyst. Environ., 164, 80–99, doi:10.1016/j.agee.2012.10.001, 2013. 1060, 1062, 1066, 1089, 1094
Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, Global Biogeochem. Cy., 23, GB2023, doi:10.1029/2008GB003327, 2009. 1066

ESDD
6, 1047–1100, 2015

Soil C management, large-scale Earth system modelling

S. Olin et al.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, B. Am. Meteorol. Soc., 93, 485–498, doi:10.1175/BAMS-D-11-00094.1, 2011. 1058
Thornton, P. E., Doney, S. C., Lindsay, K., Moore, J. K., Mahowald, N., Randerson, J. T., Fung, I., Lamarque, J.-F., Feddema, J. J., and Lee, Y.-H.: Carbon-nitrogen interactions regulate climate-carbon cycle feedbacks: results from an atmosphere-ocean general circulation model, Biogeosciences, 6, 2099–2120, doi:10.5194/bg-6-2099-2009, 2009. 1051
Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S.: Agricultural sustainability and intensive production practices, Nature, 418, 671–677, doi:10.1038/nature01014, 2002. 1050, 1052
Todd-Brown, K. E. O., Randerson, J. T., Post, W. M., Hoffman, F. M., Tarnocai, C., Schuur, E. A. G., and Allison, S. D.: Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations, Biogeosciences, 10, 1717–1736, doi:10.5194/bg-10-1717-2013, 2013. 1065
Vitousek, P. M., Mooney, H. A., Lubchenco, J., and Melillo, J. M.: Human domination of earth's ecosystems, Science, 277, 494–499, doi:10.1126/science.277.5325.494, 1997. 1050
Waha, K., van Bussel, L. G. J., Muller, C., and Bondeau, A.: Climate-driven simulation of global crop sowing dates, Global Ecol. Biogeogr., 21, 247–259, doi:10.1111/j.1466-8238.2011.00678.x, 2011. 1055
Waha, K., Müller, C., Bondeau, A., Dietrich, J., Kurukulasuriya, P., Heinke, J., and Lotze-Campen, H.: Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa, Global Environ. Chang., 23, 130–143, doi:10.1016/j.gloenvcha.2012.11.001, 2013. 1067
Wania, R., Ross, I., and Prentice, I. C.: Integrating peatlands and permafrost into a dynamic global vegetation model: 1. Evaluation and sensitivity of physical land surface processes, Global Biogeochem. Cy., 23, GB3014, doi:10.1029/2008GB003412, 2009. 1066
Wårlind, D., Smith, B., Hickler, T., and Arneth, A.: Nitrogen feedbacks increase future terrestrial ecosystem carbon uptake in an individual-based dynamic vegetation model, Biogeosciences, 11, 6131–6146, doi:10.5194/bg-11-6131-2014, 2014. 1051, 1059
Wilhelm, W. W., Johnson, J. M. F., Hatfield, J. L., Voorhees, W. B., and Linden, D. R.: Crop and soil productivity response to corn residue removal, this paper is a joint contribution of the USDA-ARS and the Agricultural Research Division of the University of Nebraska, published as Journal Ser. no. 13949., Agron. J., 96, 1–17, 2004. 1072

ESDD
6, 1047–1100, 2015

Soil C management, large-scale Earth system modelling

S. Olin et al.

Wramneby, A., Smith, B., Zaehle, S., and Sykes, M. T.: Parameter uncertainties in the modelling of vegetation dynamics – effects on tree community structure and ecosystem functioning in European forest biomes, Ecol. Model., 216, 277–290, doi:10.1016/j.ecolmodel.2008.04.013, 2008. 1056

Yang, X., Wittig, V., Jain, A. K., and Post, W.: Integration of nitrogen cycle dynamics into the Integrated Science Assessment Model for the study of terrestrial ecosystem responses to global change, Global Biogeochem. Cy., 23, GB3474, doi:10.1029/2009GB003474, 2009. 1069

Zaehle, S. and Dalmonech, D.: Carbon–nitrogen interactions on land at global scales: current understanding in modelling climate biosphere feedbacks, Current Op. Environ. Sustain., 3, 311–320, doi:10.1016/j.cosust.2011.08.008, carbon and nitrogen cycles, 2011. 1051

Zaehle, S., Friedlingstein, P., and Friend, A. D.: Terrestrial nitrogen feedbacks may accelerate future climate change, Geophys. Res. Lett., 37, L01401, doi:10.1029/2009GL041345, 2010a. 1059, 1099

Zaehle, S., Friend, A. D., Friedlingstein, P., Dentener, F., Peylin, P., and Schulz, M.: Carbon and nitrogen cycle dynamics in the O-CN land surface model: 2. Role of the nitrogen cycle in the historical terrestrial carbon balance, Global Biogeochem. Cy., 24, GB3522, doi:10.1029/2009GB003522, 2010b. 1069, 1070

Zaehle, S., Ciais, P., Friend, A. D., and Prieur, V.: Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions, Nat. Geosci., 4, 601–605, doi:10.1038/ngeo1207, 2011. 1050, 1051, 1068, 1072

ESDD
6, 1047–1100, 2015

Soil C management, large-scale Earth system modelling

S. Olin et al.

Table 1. Simulation settings used for the comparison of soil C, yields and N leaching with different agricultural managements. For implementation of full vs. moderate tillage, see Sect. 2.1.1.

Simulation	F_{std}	F_{NT}	F_{MN}	F_{CC}	F_{MT}	F_{NR}
tillage	full	no	full	full	modest	full
manure N	no	no	yes	no	no	no
cover crops	no	no	no	yes	no	no
residue removal	75	75	75	75	75	0
scenario	yes	yes	yes	yes	no	no

ESDD
6, 1047–1100, 2015
Soil C management, large-scale Earth system modelling
S. Olin et al.

Table 2. Soil C pools (0–1.5 m) in four climatic regions, observed (Batjes, 2014) and simulated, with the 0.05 and 0.95 percentiles in parenthesis. In the last two columns, the correlation coefficients and the *p* values to demonstrate that there is a positive relationship between simulated and observed values are shown.

	Soil C ($kg\,C\,m^{-2}$)			
Climatic region	Observed	Simulated	Corr.	*P*
temperate, dry	5.7 (1.3–12.0)	10.0 (1.4–27.4)	0.14	0.0479
temperate, humid	8.4 (1.9–21.2)	11.9 (5.2–26.2)	0.05	0.4686
tropical, dry	6.0 (1.7–12.8)	7.6 (2.5–16.7)	0.07	0.3427
tropical, humid	11.2 (2.5–28.7)	7.9 (3.7–16.0)	0.13	0.0504

ESDD
6, 1047–1100, 2015

Soil C management, large-scale Earth system modelling

S. Olin et al.

Table 3. Modelled global, total land and cropland soil C and N stocks and N leaching, compared to estimates from literature. References for the studies and explanations of how some of the values were derived can be found in the notes of this table. See Table 1 for abbreviations.

	Soil C, total (Pg C)		Soil N, total (Pg N)		N leach. ($Tg\,N\,yr^{-1}$)	
model	Global[a]	Cropland	Global[b]	Cropland	Global	Cropland
F_{std}	1440	148	146	16	55	44
F_{CC}	1444	151	146	16	24	12
F_{MT}	1442	150	146	16	54	42
F_{NT}	1447	154	146	17	53	41
F_{MN}	1442	150	146	16	54	42
F_{NR}	1443	151	146	16	66	54
F_{PNV}	1385		139		18	
Other studies	1993–2456[c] 1500–2400[d]	171[e]	133–140[f]		50[g] 80[h]	14–24[i] 23[j]

[a] These numbers are without litter, soil C including litter is (1668, 1671 Pg C) for F_{std} and F_{PNV} respectively.
[b] These numbers are without litter, soil N including litter is (147, 140 Pg N) for F_{std} and F_{PNV} respectively.
[c] Stockmann et al. (2013).
[d] Ciais et al. (2013).
[e] Stockmann et al. (2013), estimate for 0–2 m, 184 Pg C and 0–1 m, 157 Pg C.
[f] Batjes (2014).
[g] Estimated from Fig. 4 in Boyer et al. (2006), 39–60 $Tg\,N\,yr^{-1}$.
[h] Gruber and Galloway (2008).
[i] Smil (1999).
[j] Liu et al. (2010).

ESDD
6, 1047–1100, 2015

Table 4. The relative (%) number of cropland grid cells with a shift regarding the management practice optimal from a carbon sequestration perspective, comparing the highest SOC for 1996–2005 and for 2046–2055, for RCP 2.6 and 8.5. Also listed are, the share of the cropland grid cells with no change in the optimal C sequestration practice, and the percent of total number of grid cells that were cropland around the year 2000 in the data set from Hurtt et al. (2011). See Table 1 for abbreviations.

		Amount of grid cells (%)	
from	to	RCP 2.6	RCP 8.5
F_{std}	F_{CC}	0.7	0.7
F_{std}	F_{MN}	0.2	0.3
F_{std}	F_{NT}	1.0	0.9
F_{CC}	F_{std}	0.2	0.1
F_{CC}	F_{MN}	0.3	0.5
F_{CC}	F_{NT}	2.2	2.5
F_{MN}	F_{std}	0.0	0.0
F_{MN}	F_{CC}	0.1	0.1
F_{MN}	F_{NT}	1.3	0.4
F_{NT}	F_{std}	0.2	0.1
F_{NT}	F_{CC}	3.8	3.5
F_{NT}	F_{MN}	2.9	5.2
No change		87.2	85.6
Cropland cells		69.1	67.2

ESDD
6, 1047–1100, 2015

Soil C management, large-scale Earth system modelling

S. Olin et al.

Table A1. The parameters for the factors f_1, f_2 and f_3 in the carbon allocation scheme (Eq. A2) for spring wheat (SW), winter wheat (WW) and maize (MA).

parameter		SW	WW	MA
f_1:	a	0.62	0.53	0.24
	b	−0.02	0	1.22
	c	5.80	7.63	18.10
	d	0.55	0.55	1.12
f_2:	a	0.86	0.8	0.68
	b	0.19	0.20	−0.06
	c	28.65	13.99	12.48
	d	0.55	0.55	0.81
f_3:	a	0	0	0
	b	1	1	1
	c	8.27	8.32	28.52
	d	1.10	1.15	1.03

ESDD
6, 1047–1100, 2015

Table A2. CFT specific parameters of Specific Leaf Area (SLA), minimum C : N value of the leaves and the amount of the total N that is applied at the different developmental atages (DS), where DS = 0 is sowing, DS = 0.5 is half way into the vegetative phase. At DS = 0.9 the rest is applied, see Olin et al. (2015) for more details.

parameter	SW	WW	MA	Unit	Reference
SLA	35	35	45	$m^2\,kg^{-1}\,C^{-1}$	
$C:N_{min}$	15	15	15	$kg\,C\,kg^{-1}\,N^{-1}$	
$N_{app,DS=0}$	0.11	0.08	0.11	fraction	Olin et al. (2015)
$N_{app,DS=0.5}$	0.50	0.19	0.50	fraction	Olin et al. (2015)

ESDD
6, 1047–1100, 2015

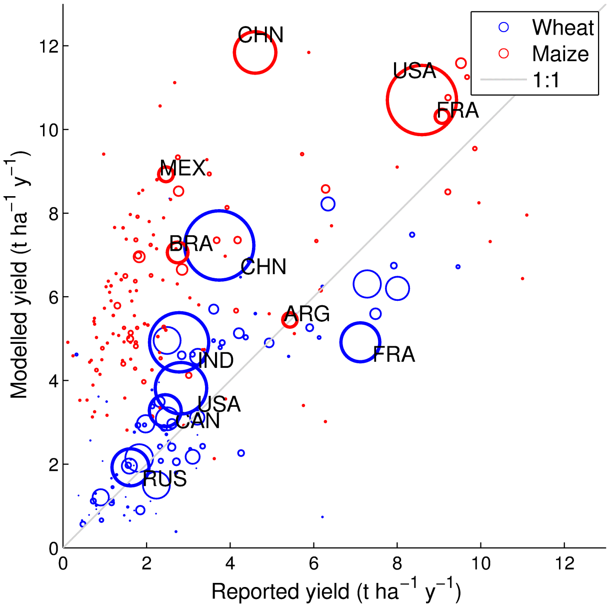

Figure 1. Per country comparison of simulated yields for WW (wheat) and MA (maize) against reported yields from FAO (1996–2005). Marker size indicates each country's total production. The top 6 producer countries of both crops are labelled with an abbreviation: ARG, Argentina; BRA, Brazil; CAN, Canada; CHN, China; FRA, France; IND, India; MEX, Mexico; RUS, Russia; USA, United States.

ESDD
6, 1047–1100, 2015

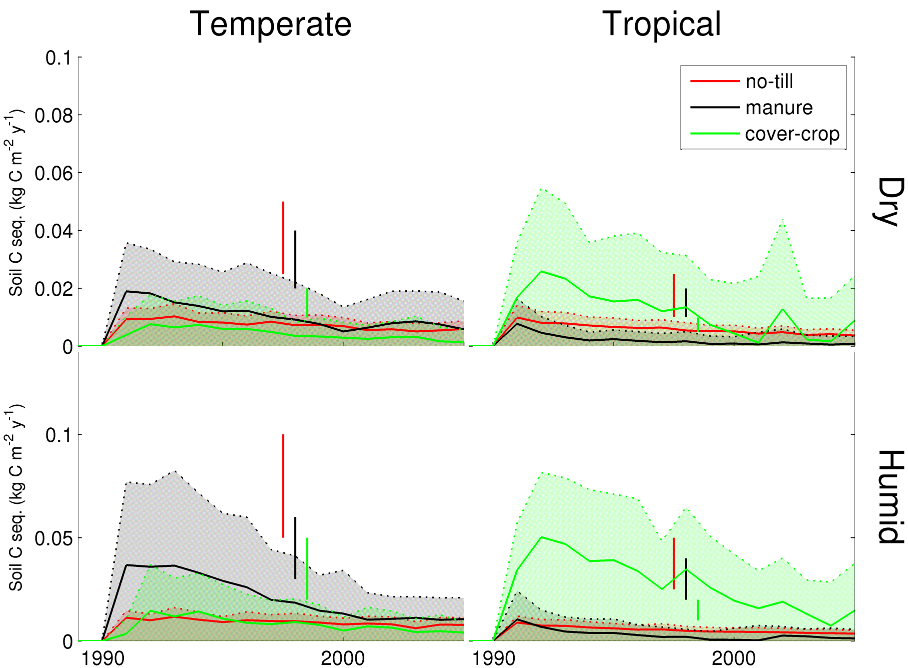

Figure 2. Simulated mean C sequestration following the implementation of management over the CRU historic period on agricultural soils averaged (thick lines) for the selected grid cells in the four climatic regions, compared to estimates (horizontal lines) from Stockmann et al. (2013). Dotted lines indicate the mean plus 2 standard deviations from all grid cells in each climatic region. The vertical lines do not represent specific years, but the potential over time to sequester C on cropland soils.

ESDD
6, 1047–1100, 2015

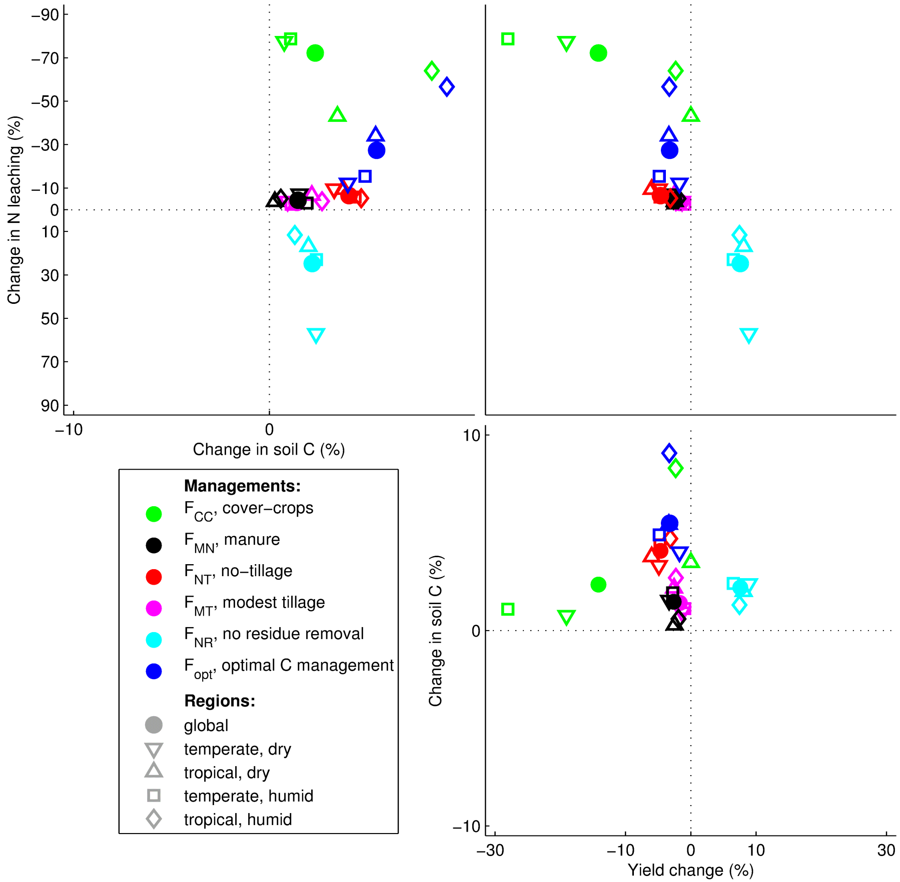

Figure 3. The simulated relative response (%) of soil carbon to management options (Table. 1) compared to the standard setup, averaged for 1996–2005 and displayed as the global response (filled symbol) and per climatic region. Note the reversed axes for N leaching (all axes display scales from reduced to enhanced ecosystem services).

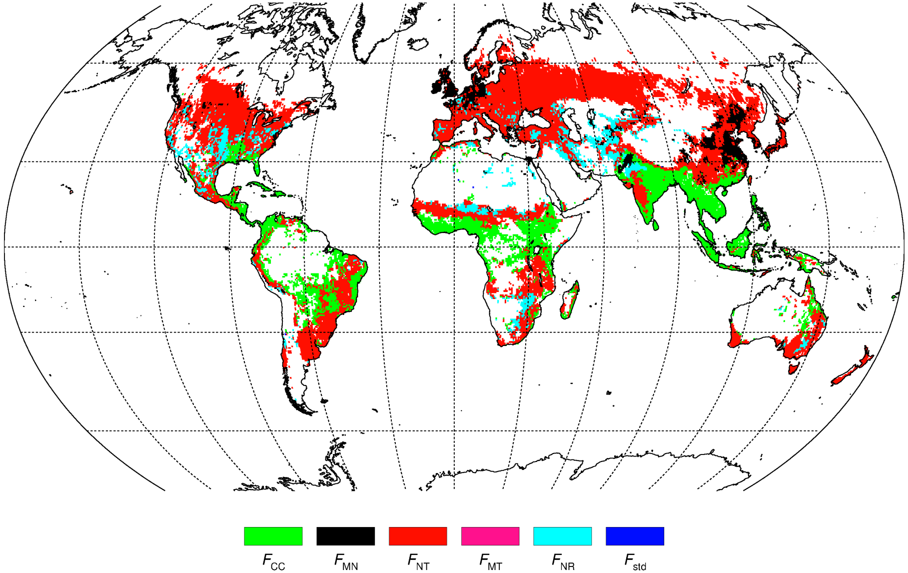

Figure 4. Optimal carbon sequestration practice around the year 2000, as simulated by LPJ-GUESS. The standard setup (F_{std}, blue) was selected when none of the other managements gave an increase in the amount of carbon sequestered. The C sequestered compared to F_{std} for choosing the optimal practice in each grid cell is 7.7 Pg C from 1750 to 2000, the reduction in global N leaching for best C sequestration practices is 11.9 Tg N yr^{-1}.

ESDD
6, 1047–1100, 2015

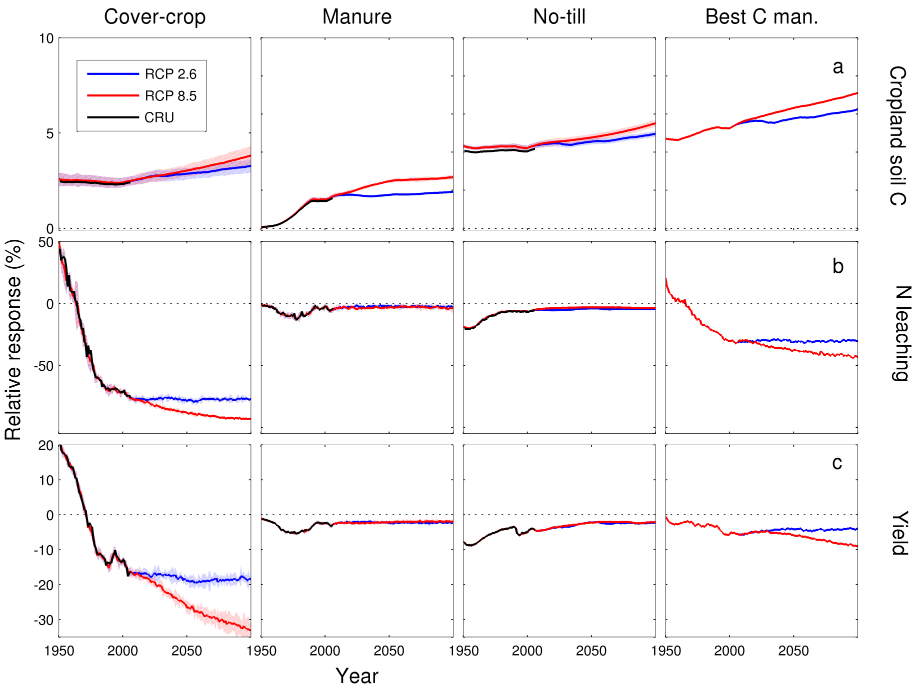

Figure 5. The simulated response on **(a)** global C in cropland soils, **(b)** yields and **(c)** N leaching with management options implemented in LPJ-GUESS relative to the standard setup. Black line, the response with historic climate (CRU), in red and blue the mean between simulations using 4 GCMs (described in Sect. 2.2) for RCPs 2.6 and 8.5 respectively, shaded areas shows the mean ±2 standard deviations. In the panels to the right, the results from choosing the best SOC management compared to the standard for the two RCPs.

ESDD
6, 1047–1100, 2015

Soil C management, large-scale Earth system modelling

S. Olin et al.

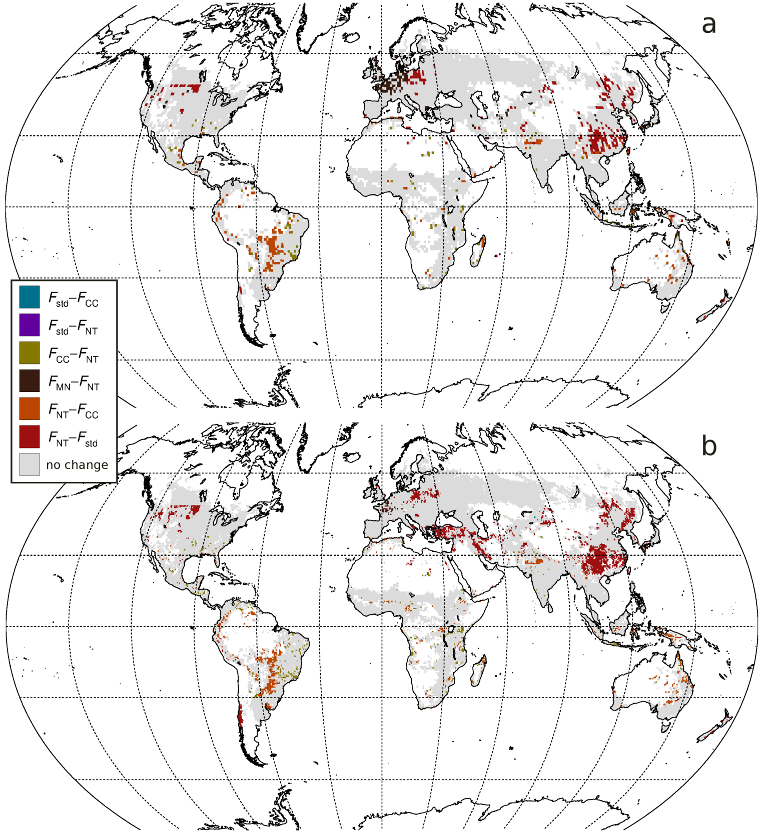

Figure 6. Grid cells where different management options resulted in the highest soil carbon in 2000 (Fig. 4) compared to 2050, **(a)** RCP 2.6 and **(b)** 8.5.

ESDD

6, 1047–1100, 2015

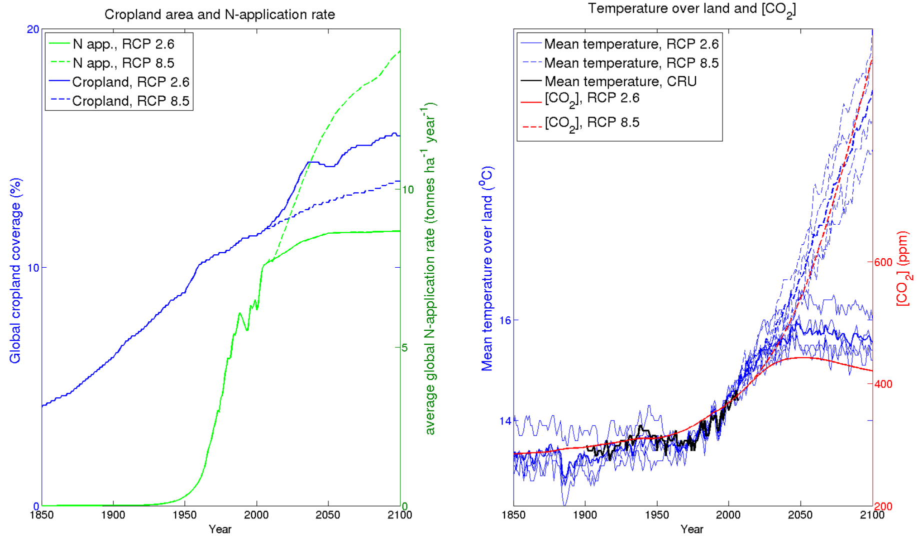

Figure B1. Input used for the simulations over the historic and scenario (RCP 2.6 and 85) periods. **(a)**, Global cropland cover (%) from (Hurtt et al., 2011), mean N fertiliser application rate (Stocker et al., 2013; Zaehle et al., 2010a); **(b)**, [CO_2] and mean terrestrial temperature from the 4 GCMs (Sect. 2.2).

ESDD
6, 1047–1100, 2015

Soil C management, large-scale Earth system modelling

S. Olin et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◄ ►
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

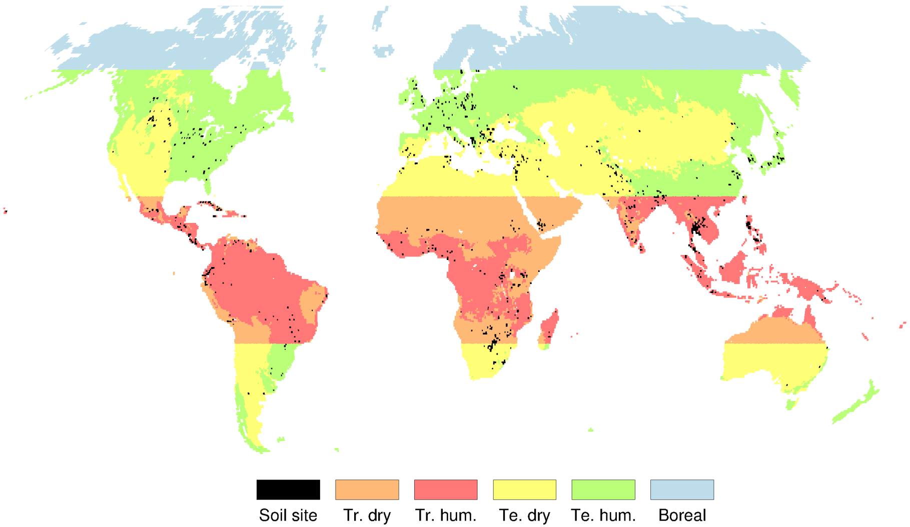

Figure B2. Climatic regions, as defined in Sect. 2.2.1 (Tropical dry, Tropical humid, Temperate dry, Temperate humid, Boreal), black pixels show the cropland soil column sites from Batjes (2005), used in the soil carbon comparison.

ESDD
6, 1047–1100, 2015

Soil C management, large-scale Earth system modelling

S. Olin et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion