Title: Potentials to mitigate greenhouse gas emissions from Swiss agriculture

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Abstract

There is an urgent need to identify and evaluate management practices for their biophysical potential to maintain productivity under climate change while mitigating greenhouse gas (GHG) emissions from individual cropping systems under specific pedo-climatic conditions. Here, we examined, through DayCent modeling, the long-term impact of soil management practices and their interactions on soil GHG emissions and GHG intensity from Swiss cropping systems. Based on experimental data from four long-term experimental sites in Switzerland (Therwil, Frick, Changins, and Reckenholz), we robustly parameterized and evaluated the model for simulating crop productivity, soil C dynamics and soil N_2O emissions across a range of management practices and pedo-climatic conditions. Net soil GHG emissions (NSGHGE) were derived from changes in soil C, N_2O emissions and CH_4 oxidation. Soils under conventional management acted as a net source of soil GHG emissions (1361–1792 kg CO_2eq ha^{-1} yr^{-1}) and NSGHGE were dominated by N_2O (50 – 63%). Reduced tillage and no-tillage reduced long-term NSGHGE by up to 31 and 58%, respectively. Organic farming, represented by organic fertilization, reduced NSGHGE by up to 31% compared to systems based solely on mineral fertilization. Replacement of slurries with a composted FYM led to an additional reduction in NSGHGE by 46%, although our approach considered only soil GHG emissions and thus did not take into account GHG emissions from the composting process. Cover cropping did not significantly influence NSGHGE, however vetch tended to reduce NSGHGE (-19%). The highest mitigation potential was associated with organic farming plus reduced tillage management, it reduced long-term NSGHGE by up to 128%. Soil C sequestration accounted, on average, for 89% of GHG mitigation potentials. Not all the management practices sustained crop yields. Nevertheless, composting of organic manures, reduced tillage and no-tillage effectively reduced NSGHGE and GHG intensity without a noticeable yield reduction. Our results suggest that implementation of the above soil management practices in Swiss cropping systems have a considerable potential for climate change mitigation, although time-limited.

Highlights:

- DayCent was parameterized and evaluated using data from four LTEs in Switzerland
- Organic farming with reduced tillage reduced net soil GHG emissions and also yield
- Composting, RT and NT reduced net soil GHG emissions without a yield reduction
- Soil C sequestration accounted, on average, for 89% of GHG mitigation potentials

Key words: soil management; cropping system; soil organic carbon; nitrous oxide; methane oxidation; greenhouse gas mitigation; greenhouse gas intensity; greenhouse gas sink; DayCent; biogeochemical modeling

1. Introduction

There is a global concern related to the increase in greenhouse gases (GHG) in the atmosphere, primarily CO_2, N_2O, and CH_4 and their impact on climate change. Intensification of agriculture due to technological advancement has doubled crop yields between 1970–2010, but also posed severe environmental problems (Pimentel *et al.*, 1995; FAOSTAT, 2017). Cultivation of agricultural land has caused a historical loss of 50 Pg of soil organic carbon (SOC) (Houghton, 1999). Soil and manure management, enteric fermentation, biomass burning, and rice cultivation have become the largest anthropogenic source of N_2O and CH_4, although there are regional differences in importance of these emissions sources (Smith *et al.*, 2014). In 2010, agriculture accounted for 5.0–5.8 Pg CO_2eq yr^{-1}, i.e., 10 – 12% of total global anthropogenic GHG emissions (Tubiello *et al.*, 2013; FAOSTAT, 2017). Switzerland is small, but a large part of its area (1522.7 km^2) is used for agriculture. In 2015, agriculture accounted for 12.6% (6.07 Tg CO_2eq yr^{-1}) of total Swiss GHG emissions (FOEN, 2017). Soil management, which is the second largest source, induces N_2O emissions that account for 30.9% of Swiss agricultural GHG emissions (FOEN, 2017). Reduction of these emissions therefore constitutes an important part of agriculture's GHG mitigation potential concerning climate change as well as achieving Swiss GHG reduction targets aiming to limit global climate warming below 2°C by 2100 in line with the RCP2.6 scenario (Kyoto Protocol, Lima 2014 and Paris 2015 agreements).

Research proposed a number of management options that can significantly contribute to reducing soil GHG emissions from cropping systems, such as more efficient use of fertilizers (Bouwman *et al.*, 2002; Venterea *et al.*, 2012), organic farming (Gattinger *et al.*, 2012; Skinner *et al.*, 2014), reduced tillage intensity or no-tillage (West and Marland, 2002; Six *et al.*, 2004; van Kessel *et al.*, 2013; Cooper *et al.*, 2016), residue retention, cover cropping (Poeplau and Don, 2015; Kaye and Quemada, 2017), improved water and rice management.

The biophysical mitigation potential of these practices need to be evaluated for individual cropping systems under specific pedo-climatic conditions, historical land use and management (Smith, 2012). Previous research on Swiss cropping systems has been designed to investigate the influence of a range of soil management practices on agronomic performance, SOC and soil fertility (Mäder *et al.*, 2002; Fließbach *et al.*, 2007; Berner *et al.*, 2008; Krauss *et al.*, 2010; Wittwer *et al.*, 2017). Yet, relatively little is known about effects of these practices on soil GHG emissions. Identification and quantification of GHG mitigation potentials associated with soil managements is key to designing effective agricultural mitigation strategies. In addition to evaluation of mitigation options on an area basis, more attention has been recently paid to assessment of GHG intensity (GHGI) per agricultural product unit that indicates the GHG efficiency of production (Burney *et al.*, 2010). This assessment has been allied to the concept of sustainable intensification (Godfray *et al.*, 2010; Tilman *et al.*, 2011; Smith, 2013) and promotes management practices that increase production without a commensurate increase in emissions (Smith *et al.*, 2014).

Net potential of soil management practices to contribute to GHG mitigation depends on the direction and magnitude of changes in SOC, N_2O and CH_4 emissions associated with their implementation compared to conventional practices. Direction and magnitude of soil GHG emissions and thus mitigation potentials might change over time in response to the management and climate change (Smith, 2012). Long-term field experiments (LTE) suggest that rates of SOC change in response to soil management are the greatest in the first 10 years and then attenuate when reaching a new steady-state (Johnston *et al.*, 2009; Gattinger *et al.*, 2012). Six *et al.* (2004) and van Kessel *et al.* (2013) found a noticeable time dependency in no-tillage and reduced tillage effects on N_2O emissions. Nevertheless, there is a lack of long-term observations. Most GHG studies are based on a sampling period over one to two growing seasons that does not even cover the entire crop rotation length. Soil management and crop interaction effects on soil GHG emissions can be complex and cannot be entirely identified in a short-term. This is most pronounced in complex cropping systems, like those in organic farming leading to a pronounced temporal decoupling of N input und corresponding N_2O emission (Skinner *et al.*, 2014). Therefore, there is an urgent need for long-term monitoring of management-specific GHG emissions over entire crop rotations preferably across a wide range of pedo-climatic conditions to elucidate long-term N and C dynamics in response to changes in management. However, the spatial and temporal resolution and the extent of GHG measurements are generally limited by cost and time constraints. Alternatively, ecosystem process-based models that are capable of capturing complex long-term dynamics in soil-crop-atmosphere systems, when correctly integrated with empirical data, provide effective and robust tools to bridge data gaps, to understand and quantify soil GHG emissions responses to changes in soil management. Furthermore, these models can be used to identify and evaluate long-term effects and strengths of selected GHG mitigation options and thus support climate change strategies. DayCent (Del Grosso *et al.*, 2001; Campbell and Paustrian, 2015) is a dominant coupled soil-plant dynamic model that has been widely used to simulate long-term ecosystem responses to changes in soil management and climate in the US (Parton and Rasmussen, 1994; Del Grosso *et al.*, 2008b; De Gryze *et al.*, 2011; Lee *et al.*, 2015). However, its application to European cropping systems has been limited (e.g., Foereid *et al.* (2012), Alvaro-Fuentes *et al.* (2017)). Hence, if DayCent is to be reliably used to address agriculture GHG mitigation under Swiss conditions, it requires robust parameterization for common Swiss crops and management practices and evaluation across a range of management practices and pedo-climatic conditions. Accordingly, this study was designed with the following objectives: i) to parameterize DayCent for common crops and management practices using long-term empirical data collected under various pedo-climatic conditions in Switzerland; ii) to evaluate the model’s ability to simulate long-term crop productivity, SOC dynamics and soil N_2O emissions in diverse Swiss cropping systems; and iii) to examine the long-term impact of management practices and their interactions on soil GHG emissions and GHGI at each experimental site.

2. Materials and methods

2.1 LTE descriptions

The empirical data was derived from four Swiss LTEs located in Changins (P29C LTE), Therwil (DOK LTE), Reckenholz (FAST LTE) and Frick (Frick LTE, Table 1). These LTEs have evaluated effects of various farming systems and soil management practices (Table 2). DOK LTE compares farming systems differing with respect to fertilization and plant protection management: a) biodynamic (D2) and organic (O2) systems fertilized with farmyard manure (FYM) and slurry at the typical intensity of Swiss organic farms (Mäder *et al.*, 2006); b) conventional system (K2) with the same organic fertilizer input and additional mineral fertilization up to recommended plant-specific levels; c) mineral conventional system (M2) fertilized with mineral fertilizers, representing a stockless system; and d) unfertilized system (N) (Mäder *et al.*, 2006). The N, P and K inputs in D2 and O2 were 34-51% lower than in K2 and M2 systems (Mäder *et al.*, 2002). Organic (D, O) and the conventional system (K) were managed at two fertilization levels, corresponding to 100% and 50% of typical fertilization. Systems were arranged in a split-split-plot design with four replicates. Seven-year crop rotation consisted of potatoes (*Solanum tuberosum*), green manure, winter wheat (*Triticum aestivum*), fodder intercrop, white cabbage (*Brassica oleracea*), winter wheat, winter barley (*Hordeum vulgare*) and a two-year grass-clover ley (*Trifolium pratense, Trifolium repens, Dactylis glomerata, Festuca rubra, Phleum pratense, Lolium perennne, Poa pratensis, Festuca pratensis*) (Fließbach *et al.*, 2007). White cabbage was replaced with beetroot (*Beta vulgaris*) and soybeans (*Glycine max*), and one winter cereal with silage maize

(*Zea mays)* in later years. As fodder intercrops, rye and vetch or sunflower and vetch mixtures were planted. Crop rotation was planted with a temporal shift on three rotation subplots (later referred to a rotation A, B and C) so that three crops were grown simultaneously in each system each year. Soils were managed under conventional tillage and cereal straw was removed. SOC at 0-20 cm was measured annually after crop harvest (Fließbach *et al.*, 2007). Climate data (1977-2013) were recorded at the Basel-Binningen weather station. Symbiotic N_2 fixation by soybeans, and red (*Trifolium pratense*) and white clover (*Trifolium repens*) in grass-clover ley was measured using ^{15}N natural abundance methods (Oberson *et al.*, 2007; Oberson *et al.*, 2013). Weekly soil N_2O and CH_4 emissions and mineral N (NO_3^- and NH_4^+ at 0-20 cm) from K2, M2, O2 and N systems were measured during August 2012–March 2014 (Gattinger *et al.*, 2017).

Frick LTE compares the following management factors: i) tillage practices (conventional (CT) vs. reduced (RT)); ii) type of organic fertilization (slurry alone (SL) vs. manure compost (MC)); and iii) without vs. with biodynamic compost and field preparations (Berner *et al.*, 2008). Treatments were arranged in a split-split-plot design with four replicates. Six-year crop rotation consisted of winter wheat, oat-clover (*Trifolium alexandrinum*), sunflower (*Helianthus annuus*), spelt (*Triticum spelta*), a two-year grass-clover ley (*Trifolium campestre, Dactylis glomerata, Festuca pratensis Huds., Phleum pratense , Lolium perenne*), winter pea green manure (*Pisum sativum*) and silage maize (*Zea mays*)(Krauss *et al.*, 2010). Winter pea was grown only under RT following the grass-clover incorporation. Cereal straw and intercrop were harvested (Berner *et al.*, 2008; Gadermaier *et al.*, 2012); sunflower stalks were removed only in 2010. Organic matter (OM) inputs were higher in MC than in SL, partially due to straw content. Differences in N inputs between MC and SL were driven by differences in N content of solid and liquid organic manures and N losses during the storage (Gadermaier *et al.*, 2012). The SOC at 0-10 and 10-20 cm was measured in 2002, 2005 and

2008 (Berner *et al.*, 2008; Gadermaier *et al.*, 2012). Climate data (2002-2013) were recorded at the FiBL vineyard weather station.

FAST LTE compares conventional (CON) and organic (ORG) farming systems with different tillage intensity (intensive tillage by mouldboard ploughing (IT) vs. no-tillage (NT) and reduced tillage (RT) in CON and ORG systems, respectively) and four cover crop treatments (legume (VETCH), non-legume (MUST), mixture of several species (MIX), and a control without cover crops (CONT)) (Wittwer *et al.*, 2017). Six-year crop rotation consisted of winter wheat, maize, field bean (*Vicia faba*), winter wheat and a two-year grass-clover mixture (*Trifolium pratense, Trifolium album, Dactylis glomerata, Festuca pratensis, Lolium perenne, Phleum pratense*). Due to a lack of data only first four years of the rotation were considered in the analysis. Cover crops were sown before winter wheat and maize. Crop residues (cover crops, maize and field bean) remained on plots, except for the winter wheat straw. Climate data (1981-2014) were downloaded from MeteoSwiss (2016).

P29C LTE compares four tillage practices: i) plough (PL), ii) chisel (CH), iii) cultivator (CL) and iv) rototiller (RT) on two contrasting soil textures. The CH treatment was converted to direct seeding with no-tillage after 2007. Although data from the whole experimental period were considered for model parametrization, GHG predictions only for 1978-2007 were included in analyses. SOC at 0-20 cm was measured in all treatments on 15 occasions (Büchi *et al.*, 2017). Four-year crop rotation consisted of rapeseed (*Brassica napus*), winter wheat, grain maize and winter wheat. Climate data (1969-2013) were recorded at the site.

The number of treatments, factorial design and long-term duration of LTEs provided a rich dataset for DayCent parameterization and evaluation across a range of management practices and pedo-climatic conditions in Switzerland, although only single site measurements on soil mineral N and N_2O emissions were available for evaluation of the model’s ability to simulate soil N processes. Due to a limited model representation of biodynamic amendments, biodynamic systems/treatments were neglected.

2.2 DayCent model

DayCent (version 2012)(Del Grosso *et al.*, 2001) is a fully resolved terrestrial ecosystem model of intermediate complexity that simulates C and N biogeochemical processes in various soil-plant systems. It includes sub-models for plant productivity, decomposition of dead plant material and soil organic matter (SOM), soil water and temperature dynamics, N gas fluxes and CH_4 oxidation. Net primary productivity is a function of genetic potential, plant phenology, nutrient availability, soil water, temperature, shading and solar radiation. The SOM, represented by plant litter and three conceptual pools (active, slow, and passive), is simulated for the upper 20 cm. N gas sub-model represents both denitrification and nitrification. Denitrification rates are calculated for each soil layer based on soil NO_3^-, available labile C, water content, texture, and temperature; while nitrification rates are calculated based on soil NH_4^+, water content, texture, and temperature. CH_4 oxidation is a function of soil temperature, water content, porosity, and field capacity. DayCent has been shown to accurately simulate crop yields, soil C and N dynamics, and N_2O emissions when rigorously calibrated and evaluated against empirical data representing various ecosystems and pedo-climatic conditions (Paustian *et al.*, 1997; Del Grosso *et al.*, 2005; Del Grosso *et al.*, 2008a).

2.3 Modeling approach

Model parameterization: Model parameterization was accomplished using an inverse modeling package PEST (version 13.0) (Doherty and Hunt, 2010) that iteratively estimates parameter values using a nonlinear regression method based on the principle of least-squares minimization. Details on coupling DayCent with PEST have been reported by Necpalova *et al.* (2015).

Parametrization dataset comprised time series of crop yields (n = 2618) and SOC contents (n = 1284) collected across 46 treatments and 19 crops at four sites. Model integration with empirical data was evaluated using a weighted multicomponent objective function represented by weighted least-squared difference between measured and simulated values. Crop-specific and SOC data formed independent components of the objective function. The inter-component weighting strategy was defined such that each component contributed equally to the objective function at the start of parametrization, regardless of the number of measurements per component, units, and other confounding factors. Individual measurements within each component were weighted equally.

Initially, a local sensitivity analysis of model parameters at their default values identified parameters sensitive to the parametrization dataset. The sensitivity was derived from the first-order partial derivatives of simulated values corresponding to available empirical data with respect to selected uncertain parameters. Temperature response functions and nutrient limitations were parametrized at the crop-species level, while the genetic growth potential and maximum harvest index were adjusted at the crop cultivar level. A list of selected model parameters and their uncertainty ranges are listed in Table A.1.

Default parameter values were considered as initial values, their uncertainty ranges were derived from the literature review and our prior knowledge. All parameters were log-transformed to strengthen linear relationships between parameters and simulated values. Prior to the parameterization, we observed a large number of correlations between parameters in the correlation coefficient matrix. Therefore, the parameterization was achieved in several independent stages. Firstly, crop parameters were inferred from crop productivity data collected under conventional management practices. Secondly, tillage decomposition multipliers for individual SOM pools were inferred from long-term SOC data collected under various tillage managements and under mineral fertilization. Lastly, bio-chemical composition of organic fertilizers was inferred from long-term crop productivity and SOC data collected under organic fertilization. Each stage was based on a specific subset of the parametrization dataset, while remaining data were assigned 0 weights, and thus did not contribute to the overall objective function computed for the individual stages of parametrization. Model parameters adjusted in the initial stages were frozen at their values for the later stages of parametrization. Parameterization runs across numerous treatments and four sites reduced uncertainty ranges for selected parameters and delivered arithmetic means and confidence intervals considered in the model application. Due to a lack of yield data, Persian and red clover intercrops, green manures at DOK, winter rye, sunflower-summer vetch, and clover-mustard mixtures remained represented by default values in the model application. To retain the model widely applicable, the parameterization was kept as general as possible across the sites.

Spin-up simulations: Distribution of modeled SOM pools was initialized using spin-up simulations of native temperate deciduous forest (0-1399), already strongly influenced by human activities (Pfister, 1995), that brought SOM pools into equilibrium with OM inputs. Simulations proceed from equilibrium with base simulations of historical land use management in the following periods (Bürgi *et al.*, 2015; Bürgi, 2016): 1) appearance of agriculture (1400 - 1750; winter grain - summer grain - fallow rotations and limited manure inputs), 2) agricultural revolution (1751 - 1850; introduction of improved seeds, planting clover in fallow fields, replacement of summer grains by potatoes, cultivation of formerly uncultivated land due to excessive drainage and higher availability of organic manures due to higher number of animals), 3) agricultural intensification (1851 - 1950; manufacturing of mineral fertilizer that provided supplemental fertilization), and 4) modern agriculture (from 1950; introduction of maize and diverse crop rotations with three grass-clover ley years). Due to a scarcity of site-specific data, the land use history was assumed to be identical for all sites, although the last period finished in different years depending on the LTE establishment year. Initial measurements of site-specific SOC content were used by an inverse modeling algorithm to adjust the forest radiation use efficiency for calculating potential productivity to reach pre-experimental SOC content at each site. For these simulations, site-specific climate data was used recursively. Following base simulations, the model simulated long-term soil management effects as imposed in treatments established in LTEs. These simulations started when the actual LTEs were established and continued until the end of the experimental period.

Long-term simulations: Parameterized DayCent was used to simulate crop yields, SOC dynamics, N_2O emissions and CH_4 oxidation capacity for individual treatments under site-specific pedo-climatic conditions at each site over 30 years. The model was driven by recorded management, soil physicochemical properties and daily climate data. If the LTE was shorter than 30 years, the management and climate data were used repeatedly until the end of the simulation period. Simulations were run independently by replicate, as soil profiles were characterized at the plot level, except for P29C and Frick, where only average soil properties were available. Soil hydraulic properties (field capacity, wilting point and saturated hydraulic conductivity) were calculated based on soil texture, bulk density and SOC concentration using pedo-transfer functions (Wosten *et al.*, 1999). Soil physical properties were assumed to be constant over time, i.e., SOC content was computed on an equivalent mass basis using initial bulk densities. For all crops, yields, straw and aboveground biomass was expressed on a C content basis using published crop-specific plant component C concentrations. Crop productivity and SOC content data were equally divided into two independent datasets, for model parameterization and evaluation, based on blocking in the experimental design. Soil properties were available for all plot replicates, thus half of the plot replicates was used for model calibration and the other half for model evaluation with the assumption that blocking was effective and arrangement of the blocks reflected variability in soil properties at each LTE. Additionally, soil NO_3^-, NH_4^+ and N_2O data from DOK were considered for the evaluation of the model's ability to simulate soil N processes.

2.4 Model evaluation, calculations, and statistical analysis

Model's ability to simulate crop productivity, long-term SOC, soil NH_4^+ and NO_3^-, daily and cumulative N_2O emissions was quantified using multiple statistical criteria (Wallach *et al.*, 2014): root mean square error (RMSE), relative RMSE (rRMSE), coefficient of determination (r^2) and Willmott's index (WI).

Net soil GHG emissions (NSGHGE, kg CO_2eq ha^{-1} yr^{-1}) were derived from annual changes in SOC content, N_2O emissions and CH_4 oxidation capacity using 100-year time horizon global warming potentials (IPCC, 2014) as follows:

$$\mathrm{NSGHGE} = \frac{44}{12} \times [\Delta\mathrm{SOC}] + 265 \times [\mathrm{N_2O}] - 28 \times [\mathrm{CH_4}]$$

where [ΔSOC] is the change in SOC content (kg C ha^{-1} yr^{-1}), [N_2O] is N_2O cumulative flux (kg N_2O ha^{-1} yr^{-1}) and [CH_4] is CH_4 uptake (kg CH_4 ha^{-1} yr^{-1}). Indirect N_2O emissions were not considered due to high uncertainties associated with their estimates and a lack of reliable evaluation data for Swiss conditions.

Due to an implementation of complex crop rotations causing a discrepancy between the growing season of main crops and a period considered for NSGHGE calculation, GHGI (kg

CO_2eq kg^{-1} yield) was computed as the sum of annual NSGHGE over 30 years, divided by total harvested grain, tuber, vegetables and forages (kg DM ha^{-1}) over 30 years:

$$\mathrm{GHGI} = \frac{\sum_{\mathrm{i}=1}^{30} \mathrm{NSGHGE}}{\sum_{\mathrm{i}=1}^{30} \mathrm{yield}}$$

If the experimental period was longer than 30 years, only last 30 years were considered in the analysis. Management effects and their interactions were determined statistically using linear mixed-effects models in SAS (2014) with time included as a random effect and other factors and their interactions as fixed effects. Linear regression analysis was used to compute the annual change in SOC content over time corresponding to a slope of the regression line.

3. Results

3.1 Model evaluation

Following the parameterization, DayCent reproduced 81% of the measured variation in crop productivity across years, treatments and sites (RMSE = 76 g C m^{-2}, rRMSE = 0.29). Productivity predictions were more certain for Frick and FAST and less certain for P29C (Fig.1). The model substantially underpredicted the measured variation in productivity due to spatial replication. Mean crop-specific productivity across years, treatments and sites was simulated adequately (Table 3). Nevertheless, the model noticeably underpredicted productivity of winter peas, mixture, white mustard, potatoes and overpredicted rapeseed productivity. As indicated by r^2, it substantially underpredicted the measured variation in spelt, winter barley, white cabbage, field beans and potatoes productivity. The highest rRMSE was associated with productivity predictions of tuber crops, winter peas, spelt and white cabbage.

DayCent predicted treatment-associated crop productivity satisfactorily (Fig.2). Nevertheless, it overpredicted productivity for N system in DOK, PL treatment on loam soil in P29C, and underpredicted productivity for ORG-RT treatments with mixture and vetch cover cropping in FAST. The model reproduced most of the variation in measured productivity within each treatment ($r^2 > 0.6$), except for N system in DOK and CH treatment on clay soil in P29C. The rRMSE associated with productivity predictions was below 0.4 for all modeled treatments, excluding N system in DOK.

For SOC content, the model reproduced 76% of the measured variation across years, treatments and sites (RMSE = 504 g C m^{-2}, rRMSE = 0.13; Fig.3a). It also reproduced 63% of the measured variation in treatment-induced SOC change over time, although it substantially underpredicted higher SOC losses (Fig.3b), particularly for N, M2, K2 and K1 systems, all in rotation A in DOK (Fig.B1), and PL treatment on clay soil in P29C (Fig.B2). Although r^2 greatly varied between treatments, rRMSE associated with SOC predictions was consistently below 0.23 (Fig.2).

Soil N_2O emissions were evaluated against measured data collected in four main systems in DOK over 1.5 years. DayCent predicted 25% of the measured variation in daily N_2O emissions. Soil N_2O predictions for grass-clover and silage maize were adequate, although less certain for green manure (Fig.4). While the error associated with daily emissions was high (RMSE = 19.89 g N m^{-2}; rRMSE = 1.73), the model predicted measured variation and magnitude of cumulative N_2O emissions across all systems satisfactorily (Fig.5).

Soil NO_3^- and NH_4^+ data from the same systems were used to evaluate model predictions of soil N dynamics. The model reproduced 73% and 42% of the measured variation in soil NO_3^- and NH_4^+ concentrations, respectively, across all systems. However, it substantially overpredicted soil NH_4^+ and underpredicted soil NO_3^-, particularly after both mineral and organic fertilization events. This amplified the overall predictive error for soil NO_3^- and NH_4^+ (Fig.B3).

There was no field data available to validate modeled CH_4 uptake at Swiss LTEs, therefore the magnitude of the model's predictions was evaluated with the results from peer-reviewed studies conducted on temperate agricultural soils (Flessa *et al.*, 1995; Smith *et al.*, 2000; Hütsch, 2001; Skinner *et al.*, 2014).

3.2 Soil GHG emissions and mitigation potentials

Tillage treatments and differences in soil texture did not significantly influence soil CO_2 emissions in P29C LTE (Table 4). Soils under all treatments acted as a net CO_2 source (Fig.6). The SOC decrease in response to tillage intensities was consistent across two soil textures and followed the order: PL > CH = CL > RO. The rate of decrease was higher for clay than for loam soil (Table 5). In comparison, soil N_2O emissions exhibited sensitivity to tillage intensities and soil texture (Fig.6, Table 4). They decreased in the order: PL > CH> CL > RO, and were significantly higher from clay than from loam soil (Fig.6). The proportion of N inputs lost as N_2O ranged from 1.24 to 1.35% for loam and from 1.36 to 1.53% for clay. All reduced tillage treatments were more effective in reducing N_2O emissions from clay than from loam soil.

NSGHGE for P29C ranged from 989 to 1792 kg CO_2eq ha^{-1} yr^{-1} with a 61% contribution from N_2O (Fig.6). The highest NSGHGE were simulated for PL treatments (Table 5). Under CH relative to PL, NSGHGE from loam decreased by 8%, and from clay by 14% (Table 6). This was mainly attributed to the reduction in soil CO_2 emissions. Similarly, CL decreased soil CO_2 emissions relative to PL treatments and thereby NSGHGE by 10 to 14% depending on soil texture. RO treatments exhibited the highest potential to reduce NSGHGE. This reduction was driven by a 49 to 50% decrease in soil CO_2 emissions and a simultaneous 9 to 11% decrease in soil N_2O emissions.

Yields were noticeably higher for loam than for clay soil, with a minor increase under RO treatments (Table 5). The GHGI, ranging from 0.22 to 0.41 kg CO_2eq kg^{-1} yield, responded to tillage intensities consistently across two soil textures. The highest GHGI was simulated for PL treatments. Reduced tillage decreased GHGI by up to 32%, with RO having the highest mitigation potential (Table 6).

For DOK LTE, two independent statistical analyses were conducted: a) N and M2 systems were excluded to include the fertilization level as a fixed factor; and b) K1 and O1 were excluded to compare all systems at their typical fertilization.

Soils under all systems acted as a net CO_2 source and the rate of SOC decrease was driven by total C inputs (Table 5), which explained 89% of the variation in SOC change. Soil CO_2 emissions were significantly higher for N than for O2 and K2 systems (Fig.6). Soil N_2O emissions were influenced by a system and level of fertilization interaction (Table 4), and decreased in the order: K2 > M2 = O2 > N with reduced fertilization reducing N_2O emissions more effectively in K1 than in O1 (Fig.6). Soil N_2O emissions were noticeably driven by total N inputs to the systems and their proportion ranged from 1.01 to 1.42% (Table 5). Soil CH_4 oxidation potential was significantly influenced by soil management, not just in DOK (Table 4).

NSGHGE in DOK ranged from 927 to 1498 kg CO_2eq ha^{-1} yr^{-1} and were not significantly different between systems (Fig.6). The average contribution of N_2O to NSGHGE was 60%. The highest NSGHGE were simulated for M2 and decreased in the order: M2 > K2 > N > O2 > K1 > O1 (Table 5). Implementation of K2 reduced NSGHGE by 4% relative to M2, resulting from a 64% decrease in soil CO_2 emissions but a simultaneous 44% increase in soil

N_2O emissions (Table 6). When fertilizer inputs were reduced to 50% of typical fertilization, K1 decreased both N_2O and CO_2 emissions, and led to a 21% reduction in NSGHGE. Adoption of O2 reduced NSGHGE by 18%, primarily due to a 37% reduction in soil CO_2 emissions. In comparison, there was an overall decrease in NSGHGE by 24% for O1, mainly due to a 35% reduction in soil N_2O emissions relative to M2. N system reduced soil N_2O emissions by 59% but increased soil CO_2 emissions by 41% relative to M2, thus the overall reduction in NSGHGE was only 16%.

Crop yields were influenced by system and fertilization level (Table 4), and decreased in the order: K2 > M2 > O2 > K1 > O1 > N. The GHGI for these systems ranged from 0.13 to 0.20 kg CO_2eq kg^{-1} yield (Table 5). Implementation of K2 and O2 led to a GHGI reduction by 11 and 16%, respectively. The reduction in fertilization intensity in K1 led to a further reduction in GHGI, which was not observed for O1 system (Tables 5 and 6).

In FAST LTE, soil CO_2 emissions were significantly affected by a system and tillage interaction (Table 4) and decreased in the order: CON-IT > CON-NT = ORG-IT > ORG-RT (Fig.6). Soils under all treatments, except for ORG-RT, acted as a net CO_2 source. Total C inputs controlled rates of SOC change under RT and NT treatments, explaining 95 and 89% variation in SOC changes, respectively. Soil N_2O emissions were influenced by a system and tillage interaction and cover cropping (Table 4), and decreased in the order: ORG-IT > CON-IT = ORG-RT > CON-NT, with NT reducing N_2O emissions more effectively in CON system than RT in ORG system (Fig.6). Soil N_2O emissions under vetch were significantly higher than those from other cover crop treatments, and were strongly correlated with total N inputs for IT treatments. However, there was no relationship observed with total N inputs for NT and RT treatments. The proportion of total N inputs lost as N_2O ranged from 0.80% to 1.09% (Table 5).

NSGHGE for FAST ranged from -594 to 1397 kg CO_2eq ha^{-1} yr^{-1} and were significantly affected by a system and tillage interaction (Table 4). The average N_2O contribution to positive NSGHGE was 63%. The highest NSGHGE were simulated for CON-IT treatment and decreased in the order: CON-IT > ORG-IT = CON-NT > ORG-RT, with ORG-RT reducing NSGHGE twice more effectively than CON-NT treatment (Table 5). Mustard and mixture cover cropping reduced NSGHGE by 6 to 10% relative to CON-IT-CONT, mainly due to a 10 to 15% reduction in soil CO_2 emissions (Table 6). Vetch cover crop reduced soil CO_2 emissions by 35%, but increased soil N_2O emissions, thus the overall reduction in NSGHGE was only 19% relative to CON-IT-CONT. NT reduced NSGHGE by 58%, relative to CON-IT, through a reduction in soil CO_2 and N_2O emissions by 76% and 22%, respectively. Cover cropping in combination with NT reduced the mitigation potential of NT. Implementation of ORG reduced NSGHGE by 31%, primarily due to a 51% reduction in soil CO_2 emissions. ORG in combination with cover cropping, particularly with vetch, decreased NSGHGE even more. This was mainly attributed to a higher reduction in soil CO_2 emissions. Furthermore, the reduction in CO_2 emissions was doubled when ORG was implemented with RT. This ORG-RT combination led to a 128% reduction in NSGHGE compared to CON-IT and thereby turned the cropping system into a net GHG sink. Additional strengthening of the sink potential induced by ORG-RT management was simulated in combination with vetch cover cropping (Table 6).

Yields in FAST were influenced by a system and tillage interaction and cover cropping (Table 4), and decreased in the order: CON-IT > CON-NT = ORG-IT > ORG-RT, with lower yield reduction due to NT in CON system than due to RT in ORG system (Table 5). Cover cropping had a positive effect on yields; i.e., mustard and mixture significantly increased yields by 4%, and vetch by 14% on average. The GHGI ranged from -0.19 to 0.35 kg CO_2eq kg^{-1} yield (Table 5). NT reduced GHGI by 56%, ORG by 20%, and the ORG-RT combination exhibited the highest potential to reduce GHGI relative to CON-IT treatment (Table 6). Use of cover crops, vetch in particular, effectively reduced GHGI when applied with IT. Conversely, no GHGI reduction was observed for cover cropping under NT or RT management.

In Frick, soil CO_2 emissions were significantly affected by the type of organic fertilization (Table 4); i.e., soil CO_2 emissions from SL were significantly higher than from MC treatments. Soils under all treatments, except for RT-MC, acted as a net CO_2 source. The rate of SOC change was driven by total C inputs. SL treatments received about 42% less C inputs in organic fertilizers (consistent with Berner *et al.* (2008)), but 12% more C in crop residues due to a slightly higher productivity. Soil N_2O emissions were also affected by the type of organic fertilization (Table 4); i.e., soil N_2O emissions from SL were higher than those from MC irrespectively of the tillage management (Fig.6). Total N inputs were comparable between fertilization treatments, i.e., SL received 19% more N in organic fertilizers, while MC received 29% more N through biological fixation. The proportion of N inputs lost as N_2O emissions was 1.75 and 1.96%, for MC and SL treatments, respectively (Table 5).
The type of organic fertilization had a significant effect on NSGHGE ranging from 661 to 1654 kg CO_2eq ha^{-1} yr^{-1} (Table 6). The highest NSGHGE were simulated for CT-SL treatment and decreased in the order: CT-SL > RT-SL > CT-MC > RT-MC (Table 5). The average N_2O contribution to NSGHGE was 80%. Replacement of SL with MC reduced NSGHGE by 46%, through a decrease in both soil CO_2 emissions by 80% and soil N_2O emissions by 13% (Table 6). Implementation of RT led to a 13% reduction in NSGHGE relative to CT-SL. This reduction was mainly attributed to a 27% decrease in soil CO_2 emissions. The highest reduction in NSGHGE was observed for the RT-MC combination. This was driven by a 108%

decrease in soil CO_2 emissions turning the system into a net CO_2 sink, and a simultaneous 13% decrease in N_2O emissions.

Yields were mainly affected by tillage management, where RT significantly increased yields by about 4%. The GHGI ranged from 0.09 to 0.23 kg CO_2eq kg^{-1} yield (Table 5). Replacement of SL with MC reduced GHGI by 45%, and RT reduced GHGI by 16%. The RT-MC combination exhibited the highest mitigation potential by decreasing GHGI by 60% relative to CT-SL treatment (Table 6).

4. Discussion

4.1 Model evaluation

DayCent's ability to simulate crop yields was comparable with other modeling studies (Grant *et al.*, 2016; Senapati *et al.*, 2016; Dutta *et al.*, 2017). For P29C, a lack of plot-specific soil properties limited simulation of the measured yield variation induced by soil heterogeneity. However, even for sites where plot-specific soil data were available and data per replicate plot were modeled independently, the model underpredicted the measured yield variation due to spatial replication. This suggests that ecosystem factors and processes not represented in the model (e.g., pests, diseases, micronutrient deficiencies, weed infestation and topography) might have a substantial influence on crop yields under field conditions. Nevertheless, DayCent captured the most important sources of variation due to treatment effects and biophysical conditions, such as soil properties and climate.

Predictive errors generally originate from either uncertainty in the input data or from the limited representation of mechanisms in the model (Ogle *et al.*, 2006). High errors associated with yield predictions of tuber crops seem to be directly related to a simplistic representation of C allocation to belowground plant components during the growth. Similarly, errors associated with yield predictions of winter crops can be explained by the limited representation of crop vernalization in the crop growth sub-model. Larger predictive errors for cover crops and white cabbage yields, which were planted only in one or two years, can be related to a scarcity of time series data required for sufficiently robust model parameterization.

Mäder *et al.* (2002) and Mayer *et al.* (2015) reported that yields in N system in DOK have been limited by N, P and K availability and higher incidence of *Phytophora infestans* compared to other systems. Lack of model representation of these processes resulted in a higher predictive error and overprediction of yields for N system.

DayCent predicted less variation in SOC content than in yield. This can be associated with a) high uncertainties in empirical data (Fig.B1); b) default parameterization of cover crops and green manures due to data limitation that might have led to under/overprediction of C inputs; and c) reduced ability to simulate growth and biomass allocation for some crops in the rotations.

Treatment-induced changes in SOC content were underpredicted in rotation A in DOK, presumably due to exogenous factors that have not affected SOC dynamics in rotation B and C, particularly associated with the top row position of these plots in the experimental blocking (e.g., soil erosion (Siegrist *et al.*, 1998)). Underprediction of SOC change in response to PL in clay soil in P29C can be attributed to a prolonged effect of deep tillage disturbance in clays (La Scala *et al.*, 2006) whereas DayCent increases decomposition rates for SOM pools only for one month (Del Grosso *et al.*, 2011).

DayCent difficulties to replicate the measured variation in daily N_2O emissions are consistent with other N_2O modeling studies (Fang *et al.*, 2015; Senapati *et al.*, 2016). Soil N_2O emissions are highly variable in time and space due to a complex interaction of biotic and abiotic processes involving multiple drivers (Davidson *et al.*, 2000; Venterea, 2007; Castellano *et al.*, 2010; Venterea *et al.*, 2012; Zhu *et al.*, 2013). Limited representation of some key drivers (e.g., topography and spatial heterogeneity in nutrient availability) might lead to discrepancies in the timing of N_2O peaks (Del Grosso *et al.*, 2011). Additionally, DayCent underpredicted N_2O emissions from green manure crops, which can be directly related to the default crop parametrization that might have led to overprediction of their productivity. Higher error associated with soil NO_3^- and NH_4^+ predictions, particularly after fertilization events, were also reported in other studies (Del Grosso *et al.*, 2008a; Fang *et al.*, 2015; Necpalova *et al.*, 2015) suggesting that model representation of fertilization effects on mineral N pools requires further improvements.

4.2 Soil GHG emissions and mitigation potentials

DayCent substantially underpredicted the variation in measured data. Accordingly, the probability of not committing type II error, i.e., detecting statistically significant differences between management practices with the type I error of 0.05 using ANOVA, was expected to be higher for model predictions. Statistical power to detect differences in measured N_2O emissions between systems in DOK was 0.78, while for model predictions the power increased to 0.92. This should, however, not diminish the validity of our statistical analyses.

Soils under conventional managements at all sites acted as a net soil GHG source, ranging from 1361 to 1792 kg CO_2eq $ha^{-1}yr^{-1}$. Despite the consistent decrease in SOC content, NSGHGE were dominated by N_2O (50 - 63%), indicating the relative importance of N_2O over CO_2 emissions in soil GHG mitigation from Swiss cropping systems. The same has been observed for cropping systems in Europe, UK (Smith, 2012) and California (De Gryze *et al.*, 2010; De Gryze *et al.*, 2011).

Reduced tillage practices reduced the long-term SOC loss and thus CO_2 emissions by up to 50% in P29C, although this decrease was not significant. In comparison, NT significantly reduced long-term CO_2 emissions by 76% in FAST. It has been well established that both reduced tillage and NT decrease disturbance of soil aggregates and therefore lead to higher SOC stabilization compared to conventional tillage (Six *et al.*, 2000; Six and Paustian, 2014). However, recent studies involving deeper sampling depth suggest that SOC sequestration potential in NT and reduced tillage systems may have been over-estimated as the apparent increase in SOC mostly results from a vertical redistribution of C due to allocation of crop residues into the shallower soil layers (Baker *et al.*, 2007; Angers and Eriksen-Hamel, 2008; Luo *et al.*, 2010; Powlson *et al.*, 2014). Since the SOC measurements at the LTE sites were carried out only to 20 cm depth and the DayCent model has been parametrized to represent the evolution of SOC under RT based on this data, our predictions of SOC sequestration in response to reduced tillage and its role in the CO_2 emission mitigation might be overestimated.

Furthermore, our results show that reduced tillage and NT led to an 11% and 22% reduction in long-term N_2O emissions, respectively. Consequently, NSGHGE were reduced by 31% and 58% due to reduced tillage and NT over 30 years, respectively. These estimates are consistent with meta-analyses conducted on long-term effects of NT and reduced tillage on NSGHGE (Six *et al.*, 2004; van Kessel *et al.*, 2013). Six *et al.* (2004) reported that a short-term adoption of NT increased NSGHGE relative to conventional tillage primarily due to an initial increase in N_2O, but NT adoption over 20 years reduced NSGHGE. Similarly, van Kessel *et al.* (2013) reported that area and yield-scaled N_2O emissions were significantly reduced after a 10 year implementation of NT or reduced tillage relative to conventional tillage. Our results show that GHGI decreased by up to 32% due to reduced tillage and by 56% due to NT, but also a 5% reduction in the yield. Furthermore, reduced fuel consumption strengthens the GHG mitigation potential associated with the adoption of these practices (Kern and Johnson, 1993; West and Marland, 2002).

Organic farming, represented by organic fertilization, reduced long-term SOC loss and thereby CO_2 emissions by 37 and 51% in DOK and FAST, respectively. These estimates are consistent with a recent meta-analysis of 74 studies reporting that organic management has the capacity to substantially increase SOC sequestration compared with non-organic management (Gattinger *et al.*, 2012). The SOC increase was driven by total C inputs like elsewhere (e.g. Leifeld and Fuhrer (2010); Kong *et al.* (2005); Autret *et al.* (2016)). Consequently, the reduction in C inputs through organic fertilization in O1 led to a reduction in the CO_2 mitigation potential.

Although organic farming did have the capacity to reduce CO_2 over 30 years, it did not reduce N_2O emissions relative to systems relying only on mineral fertilizers. This contradicts a meta-analysis based on 12 studies reporting that organic systems reduce soil N_2O emissions relative to non-organic farming systems (Skinner *et al.*, 2014). Authors attributed this reduction to lower external and total N inputs to organic systems and reduced bioavailability of organic fertilizers. External N inputs to organic systems in FAST were, however, higher, whereas in DOK, they were slightly lower than the inputs to systems solely under mineral fertilization. However, due to differences in plant residues and biological N fixation, total N inputs to organic and conventional systems were comparable in these LTEs. Another possible explanation of inconsistency with Skinner *et al.* (2014) can be that the slow release of mineral N from organic fertilizers might lead to soil N_2O emissions after the crop growth period, which is generally not covered by GHG measurements, but accounted in the modeled results. The N_2O emissions form organic systems might be even higher if we considered indirect N_2O emissions associated with ammonia volatilization (Hristov *et al.*, 2011; Petersen and Sommer, 2011). In Switzerland, about 24% of animal manure N applied to soils is assumed to be lost as ammonia (FOEN, 2017).

Our results further indicate that N_2O emissions from organic systems were driven by total N inputs. Consequently, a 50% reduction in N inputs through organic fertilizers led to a 35% reduction in N_2O emissions, but simultaneously to a reduction in CO_2 mitigation potential, resulting in a small overall effect on NSGHGE.

Organic farming in comparison with systems based solely on mineral fertilizers reduced NSGHGE by 18% in DOK and by 31% in FAST. The inability of DayCent to represent ammonia volatilization from organic fertilizers should have also increased the nutrient availability and yield potential, and consequently led to an inferior modeled yield gap compared to results from field experimentation (De Ponti *et al.*, 2012; Seufert *et al.*, 2012). Nevertheless, organic farming led to a yield reduction by 2% in DOK and 14% in FAST, and accordingly reduced GHGI by 16 and 20%, respectively. These results are in line with a recent LCA study for FAST, which indicated that organic farming reduced overall ‘cradle to grave’ GHG emissions (excluding SOC change) by 46% and 26% on an area and a yield-unit basis, respectively (Prechsl *et al.*, 2017).

The GHG mitigation potential of organic fertilization was strengthened by OM stabilization prior to its application through composting. Replacement of slurries with a FYM composted over 4 months in Frick led to an 80% and 13% reduction in soil CO_2 and N_2O emissions, respectively. This is associated with higher C inputs and lower N availability of the composted FYM compared to the slurry. The positive effect of composted FYM on SOC and N_2O has been previously reported (Fließbach *et al.*, 2007; Powlson *et al.*, 2012). This fertilization strategy had also no effect on yield and thereby reduced GHGI by 45%. However, our assessment took into consideration only soil GHG emissions within the field boundaries and therefore additional GHG emissions associated with the composting process might partially offset the soil GHG mitigation potential on-site (Pardo *et al.*, 2015).

A strong positive interactive effect of organic farming and reduced tillage in FAST strengthened the mitigation potential of these practices as when they were applied independently. This management combination led to a 200% reduction in CO_2, while its effect on N_2O emissions was negligible. SOC sequestration completely offset N_2O emissions and turned the cropping system into a GHG sink. Consequently, GHGI was reduced by 142% relative to conventional management, despite a substantial yield reduction. Positive interaction of these practices on GHG emissions has been previously reported (De Gryze *et al.*, 2011). Nevertheless, soils under organic farming and reduced tillage in Frick did not act as a net GHG sink. This can be a result of i) an implementation of more intensive and deeper tillage practices, and ii) lower C inputs associated with residues removal and lower proportion of legumes in the rotation in Frick than in FAST (Berner *et al.*, 2008; Krauss *et al.*, 2010; Gadermaier *et al.*, 2012).

Cover crops residues represent a substantial C source that has been reported to increase SOC and thus reduce soil CO_2 emissions (Kong and Six, 2010; Poeplau and Don, 2015; Kaye and Quemada, 2017). In our study, cover cropping did not significantly reduce long-term soil CO_2 emissions, although there were some trends of decreasing CO_2 emissions in FAST. Vetch reduced CO_2 under IT by 35%, and had no effect on CO_2 emissions under NT management relative to no-cover cropping. Mustard and mixture reduced CO_2 under IT by up to 15%, while they increased CO_2 emissions by 12% under NT management. This may be due to a slower incorporation of surface residues into the soil under NT than under conventional tillage management (Six *et al.*, 2004). Tillage associated with the incorporation of cover crop residues increases SOM mineralization rates, and accordingly the net reduction in soil CO_2 emissions for cover crop and IT was substantially smaller than for the cover crop and NT combinations.

Mustard and mixture did not significantly affect long-term N_2O emissions. Vetch significantly increased N_2O emissions by 10%, most likely due to an additional N input through biological N fixation (~ 7 kg ha^{-1} yr^{-1}). Recent meta-analysis of cover crop effects on N_2O emissions indicated that legumes might increase N_2O emissions at lower N input rates more than non-legume species (Basche *et al.*, 2014). This can be associated with an increased soil mineral N via N fixation (Kaspar and Singer, 2011) and/or an increased soil N availability during decomposition of residues with low C:N ratios (Baggs *et al.*, 2006; Basche *et al.*, 2014). Furthermore, N_2O from vetch cover cropping can be driven by cover crop-derived DOC (Garland *et al.*, 2014). Although cover cropping did not significantly influence NSGHGE, vetch showed a tendency to reduce NSGHGE. Overall, cover cropping increased yields due to an improved nutrient efficiency and an additional N input through biological fixation in case of legumes. Vetch decreased GHGI by 40% on average, while the reduction in GHGI was negligible for mustard and mixture. This suggests that biological N fixation can contribute to the mitigation potential of cover cropping.

Swiss soils are drained, aerated with low soil water content, thus have limited potential to produce CH_4 emissions (Conrad, 1996). Predictions of CH_4 uptake ranged from 1.1 to 1.6 kg C ha^{-1}yr^{-1} and offset about 2.3 to 10.1% of NSGHGE across treatments and sites. Although, there was no field data available to validate modeled CH_4 uptake at Swiss LTEs, the magnitude of the model predictions is comparable with those reported for temperate agricultural soils (Smith *et al.*, 2000; Hütsch, 2001), however slightly higher than those reported by Flessa *et al.* (1995) and Skinner *et al.* (2014). This discrepancy can be attributed to insufficient measurements using chamber-based field methodologies (Smith and Dobbie, 2001; Parkin, 2008; Barton *et al.*, 2015) and seasonality of the measurements which generally cover only a crop growth period (e.g., Flessa *et al.* (2002)). Another possible explanation of this inconsistency can be the DayCent's inability to represent methanogenesis following the organic manure application (Gattinger *et al.*, 2007; Chadwick *et al.*, 2011; Gattinger *et al.*, 2017) and might therefore slightly overestimate annual CH_4 uptake. Due to a small variance around the means, the modeled oxidation potential was shown to be strongly influenced by studied management practices, perhaps through altering soil water and temperature conditions, which drive the model predictions.

Although N_2O emissions represented a substantial proportion of NSGHGE (60 - 80% across treatments and sites), management practices and their combinations evaluated in this study showed a larger mitigation potential for CO_2 than N_2O emissions, i.e., organic farming with reduced tillage, composting of organic manures, NT, reduced tillage and organic farming only. The CO_2 mitigation through SOC sequestration is considered as time-limited since the capacity of soils to sequestrate C is limited once it approaches a new equilibrium (Six *et al.*, 2004; Johnston *et al.*, 2009). Furthermore, this process is reversible. If the management is not maintained, previously sequestered C can be released back to the atmosphere (Smith *et al.*, 2014).

A significant GHG mitigation was also achieved through the reduction in N_2O emissions for the following practices: a 50% reduction in N inputs, NT, composting of organic manures, and reduced tillage. This mitigation is, on the other hand, considered permanent as the GHG emissions are avoided (Smith *et al.*, 2014).

As not only soil management but also pedo-climatic conditions control soil GHG emissions, the extent of the mitigation potential of soil management practices and their combinations should be further evaluated across a wider range of pedo-climatic conditions. Furthermore, a more comprehensive GHG assessment of Swiss cropping systems taking into account all other emissions associated with the production of fertilizers, energy use, manure storage, composting, farm machinery and livestock emissions is needed.

5. Conclusions

This present study was established on the long-term empirical data that was used to parameterize and evaluate the DayCent model for Swiss cropping systems. The model demonstrated adequate ability to simulate long-term yields and SOC dynamics in complex crop rotations, although the evaluation of its ability to simulate soil N_2O emissions and CH_4 uptake was compromised by the limited data availability and therefore requires further assessment based on higher resolution data collected over an entire crop rotation period covering a range of pedo-climatic gradients.

In this study, we evaluated the long-term impact of management practices and their interactions on soil GHGE and GHGI in order to identify and quantify potential opportunities for mitigating GHG emissions in the Swiss agricultural sector. Our results demonstrated that organic farming, particularly in combination with reduced tillage management, substantially reduced long-term NSGHGE and GHGI, but it simultaneously led to a decrease in crop yields. In contrast, composting of organic manures, reduced tillage and NT managements effectively reduced long-term NSGHGE and GHGI without a noticeable crop yield reduction (up to 5%). The least GHG mitigation potential was associated with cover cropping management, which had a minor impact on NSGHGE. Despite the relative importance of N_2O over CO_2 emissions in soil GHG mitigation, SOC sequestration accounted, on average, for

89% of GHG mitigation potentials. Thus, the conversion to the above soil management practices have a considerable potential for climate change mitigation in Swiss agriculture, without affecting the overall production levels, however this potential is not permanent.

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Table 6 Relative (%) and absolute (kg CO_2eq ha^{-1} or kg CO_2eq kg^{-1}) changes in annual soil GHG emissions in response to studied soil management combinations compared with the baseline treatment in four long-term experiments (LTEs). GHGI refers to GHG intensity. The baseline represented by the treatment with the highest soil GHG emissions on an area basis at each LTE site is denoted by underlining. Mean differences (± standard error) relative to the baseline were calculated as differences of least squares means by linear mixed effects models in SAS.

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Figure 1 Modeled vs. measured grain, straw, tuber, forage yields by crop across various years, and treatments at four long-term field experimental sites in Switzerland. Each point represents a crop-specific mean of two spatial replications for a year. The horizontal error bars refer to standard deviations around measured yields due to spatial replication, while the vertical error bars refer to standard deviations around modeled yields. N, r^2, RMSE, rRMSE, WI refer to the number of observations, coefficient of determination, root mean squared error, relative root mean squared error and Willmott's index calculated for each experimental site across all treatments, crops and years, respectively. RMSE has the same unit as the variable shown. The solid line is the 1:1 line and the dashed line is the linear regression line.

Figure 2 Mean measured and modeled crop productivity and changes in soil organic C content at the 0 to 20 cm depth by long-term experimental site and treatment across all crops and years, and error associated with model predictions. Productivity comprises of grain, straw, tuber, vegetable, forages such as silage maize and grass-clover, and cover crop biomass. The error bars refer to standard deviations around measured and modeled means. rRMSE refers to the relative root mean squared error and r^2 refers to the coefficient of determination. The annual change in soil organic C content was calculated as a slope of the linear regression over time. For FAST, no soil C data were available. For Frick, soil organic C data from three sampling occasions in 2002, 2005 and 2008 were available, and these were considered to be insufficient for the linear regression analysis.

Figure 3 Modeled vs. measured (a) soil organic C content at 0 to 20 cm across various treatments, years and four long-term field experimental sites in Switzerland. Each point represents a mean soil organic C content of two spatial replications; (b) annual changes in soil organic C content over time for each individual treatment. Each point represents a slope of the linear regression against time. N, r^2, RMSE, rRMSE and WI refer to the number of observations, coefficient of determination, root mean squared error, relative root mean squared error and Willmott's index calculated across all sites, treatments and years. RMSE has the same unit as the variable shown. The solid line is the 1:1 line and the dashed line is the linear regression line.

Figure 4 Measured and modeled daily soil N_2O emissions over time for four farming system treatments in DOK. The dashed error bars refer to standard deviations around measured daily emissions due to spatial replication. The solid error bars refer to standard deviations around modeled daily emissions. The following crops were planted during this period: grass-clover lay until 13th May 2013, silage maize between 28th May and 25th September 2013 and green manure after 9th October 2013. The measured N2O data is unpublished data obtained through Pers. Comm. with Dr. Andreas Gattinger and Colin Skinner.

Figure 5 Modeled vs. measured cumulative soil N_2O emissions by treatment in DOK. Each point represents a cumulative treatment mean. The horizontal error bars refer to standard deviations around measured emissions due to spatial replication, while the vertical error bars refer to standard deviations around modeled emissions. r^2, RMSE, rRMSE and WI refer to the coefficient of determination, root mean squared error, relative root mean squared error and Willmott's index calculated across all treatments at this site. RMSE has the same unit as the variable shown. The solid line is the 1:1 line and the dashed line is the linear regression line.

Figure 6 Mean modeled net soil greenhouse gas (GHG) emissions, as calculated from soil CO_2, N_2O and CH_4 emissions for individual treatments at four long-term experimental sites over a 30 years period. Net soil GHG emissions and individual components of net soil GHG balance are expressed in CO_2 equivalents. The error bars represent standard errors of the least squares means calculated by linear mixed effects models. Letters next to the error bars indicate which treatment means are significantly different from each other within the site-specific analysis of variance represented by the color coding. Positive soil CO_2 emissions indicate a decrease in soil organic C, while negative soil CO_2 emissions indicate soil C sequestration from the atmosphere. Negative CH_4 emissions indicate CH_4 oxidation potential.

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Table 1 Soil and climate characteristics of Swiss long-term field experimental (LTE) sites.

LTE	Location	Coordinates	Soil type	Sand (%)	Clay (%)	Soil bulk density (g m^{-3})	Soil C (%)	Soil pH	Mean annual temperature (˚C)	Mean annual precipitation (mm)
P29C	Changins (Clay)	46°24’N, 06°14’E	Calcaric Cambisol	16	46	1.17	2.92	6.2	10.2	999
	(Loam)			30	26	1.44	1.34	6.8		
DOK	Therwil near Basel	47°30'N, 7°33'E	Haplic Luvisol	12	16	1.22	1.66	6.3	9.5	791
FAST	Reckenholz near Zurich	47°26'N, 8°31'E	Calcareous Cambisol	43	23	1.48	1.44	7.3	9.4	1054
Frick	Frick	47°30’N, 8°01’E	Stagnic Eutric Cambisol	22	45	1.58	2.20	7.1	8.9	1000

Table 2 Description of management factors and levels studied in long-term field experiments (LTEs) in Switzerland. FYM refers to farm yard manure. LU refers to livestock unit.

LTE (duration)	Management factors	Levels	Description	Total N input kg N ha^{-1}	Abbreviation	No. treatments	Reference
P29C (1969-2013)	Tillage	Plough	Plough to 25 cm	90 - 168	PL	8	(Büchi *et al.*, 2017a; Büchi *et al.*, 2017b)
		Chisel until 2007, then no-tillage	Chisel to 25 cm, then 0 tillage	90 - 168	CH		
		Reduced tillage - cultivator	Cultivator to 10 to 15 cm	90 - 168	CL		
		Reduce tillage - rototiller	Rototiller or rotary harrow to 8 cm	90 - 168	RO		
DOK (1977-2013)	Farming system	Control	Unfertilized	0	N	18	(Siegrist *et al.*, 1998; Fließbach *et al.*, 2000; Mäder *et al.*, 2000; Mäder *et al.*, 2002; Mäder *et al.*, 2006; Esperschutz *et al.*, 2007; Leifeld *et al.*, 2009)
		Bio-Organic	FYM and slurry at a level of 1.2, later at 1.4 LU ha^{-1} yr^{-1}; 50%/100% fertilization	47/93	O1/O2		
		Conventional	Mixed FYM and slurry at a level of 1.2, later at 1.4 LU ha^{-1} yr^{-1} + mineral NPK; 50%/100% fertilization	75/149	K1 /K2		
		Mineral	Mineral NPK according to Swiss guidelines	125	M2**		
	Crop rotation		Three crops are planted in each system simultaneously every year		A, B, C		
FAST (2009-2013)	Farming system	Organic	Slurry at a level of 1.4 LU ha^{-1} yr^{-1}	119 - 132	ORG	16	(Prechsl *et al.*, 2017; Wittwer *et al.*, 2017)
		Conventional	Mineral fertilizer	90 - 110	CON		
	Tillage	Intensive tillage	Mouldboard plough to 20 cm		IT		
		No-tillage in CON; Reduced tillage in ORG	Crops were seeded directly into the soil Rotary harrow before wheat and rotary harrow before maize, both to 5 cm		NT and RT		
	Cover crop	Legume	Common vetch (*Vicia sativa*) before winter wheat, hairy vetch (*Vicia villosa*) before maize		VETCH		
		Non-legume	White mustard (*Sinapis alba*)		MUST		
		Mixture	Mixture of legume and non-legume spp.*		MIX		
		Control	Fallow – natural vegetation		CONT		
FRICK (2002-2013)	Tillage	Conventional	Mouldboard plough to 15 cm followed by rotary harrow to 5 cm		CT	4	(Berner *et al.*, 2008; Krauss *et al.*, 2010; Sans *et al.*, 2011; Gadermaier *et al.*, 2012; Kuntz *et al.*, 2013; Peigné *et al.*, 2013; Armengot *et al.*, 2015; Krauss *et al.*, 2017)
		Reduced	Chisel plough to 15 cm followed by rotary harrow 5 cm		RT		
	Fertilization	Manure compost supplemented with slurry	Composted farmyard manure and slurry at a level of 1.4 LU ha^{-1} yr^{-1}	~90	MC		
		Only slurry	Slurry alone at a level of 1.4 LU ha^{-1} yr^{-1}	~ 85	SL		

*containing 20% phacelia (*Phacelia tanacetifolia*), 30% Persian clover (*Trifolium resupinatum*) and 50% berseem clover (*Trifolium alexandrinum*) before winter wheat and a self-designed mixture containing 15% phacelia, 52% hairy vetch, 32% buckwheat (*Fagopyrum esculentum Moench*) and 1% camelina (*Camelina sativa*) before maize.

** unfertilized during the first crop rotation (1978-1984).

Table 3 Mean (± standard deviation) measured and modeled crop productivity by crop across all treatments, years and sites, and error associated with model predictions. N, RMSE, rRMSE, r^2 and WI refer to the number of observations, root mean squared error, relative root mean squared error, coefficient of determination and Willmott's index calculated for each simulated crop across all treatments, years and sites.

Crop	Measured	Modeled	N	RMSE	rRMSE	r^2	WI
	productivity (g C m^{-2})			(g C m^{-2})			
Winter wheat	206 ± 56	207 ± 71	1032	57	0.27	0.39	0.78
Spring wheat	130 ± 35	119 ± 29	40	25	0.20	0.55	0.82
Silage maize	694 ± 156	689 ± 191	88	124	0.18	0.58	0.80
Winter barley	172 ± 48	173 ± 36	96	46	0.27	0.16	0.64
Rapeseed	134 ± 34	156 ± 32	150	30	0.23	0.66	0.80
Beetroot	245 ± 182	270 ± 151	108	124	0.50	0.55	0.85
Grain Maize	332 ± 102	340 ± 94	176	51	0.15	0.76	0.93
Potatoes	312 ± 146	357 ± 70	168	127	0.41	0.34	0.64
White cabbage	108 ± 32	111 ± 4	24	33	0.30	0.24	0.13
Sunflower	184 ± 51	210 ± 50	20	32	0.17	0.84	0.89
Spelt	129 ±39	129 ± 23	32	48	0.37	0.07	0.21
Winter peas	87 ± 3	52	4	35	0.40	-	0.10
Soybeans	143 ± 48	154 ± 50	144	35	0.25	0.58	0.86
Field beans	193 ± 42	169 ± 13	32	42	0.22	0.33	0.55
Mixture	78 ± 13	62 ± 13	16	20	0.26	0.37	0.56
Common vetch	88 ± 24	80 ± 19	16	11	0.13	0.91	0.93
White mustard	85 ± 31	71 ± 22	16	18	0.21	0.91	0.88
Fodder intercrop	157 ± 81	169 ± 51	60	42	0.27	0.83	0.89
Grass-clover mixture	478 ± 134	495 ± 85	392	93	0.19	0.53	0.80

Table 4 Analysis of variance for the effects of management practices and their interactions on soil greenhouse gas emissions and yield at each long-term experimental (LTE) site. NSGHGE refers to net soil GHG emissions. For DOK, two independent analyses were conducted: a) we excluded unfertilized (N) and mineral (M2) treatments in order to include the level of fertilization as a fixed factor in the model statement; b) treatments at 50% fertilization (i.e., K1 and O1) were excluded, in order to compare all farming systems at their typical fertilization levels.

LTE	Factors and their interactions	df	CO_2	N_2O	CH_4 oxidation	NSGHGE	Yield
P29C	Tillage	3	0.32	<0.001	0.06	0.16	<0.01
	Soil texture	1	0.14	<0.001	<0.001	<0.05	<0.001
	Tillage x soil texture	3	0.98	0.33	0.86	0.97	0.97
DOK (excluding unfertilized and mineral treatments)	Farming system	1	0.43	<0.001	<0.001	0.53	<0.05
	Level of fertilization	1	0.26	<0.001	<0.001	0.35	<0.01
	Rotation	2	0.47	0.40	<0.001	0.38	0.44
	Farming system x level of fertilization	1	0.90	<0.001	<0.05	0.68	0.97
	Farming system x rotation	2	1.00	0.13	<0.01	0.97	0.98
	Level of fertilization x rotation	2	0.99	0.92	0.9953	0.99	0.98
	Farming system x level of fertilization x rotation	2	1.00	0.80	<0.01	1.00	0.93
DOK (excluding 50% fertilization level treatments)	Farming system	3	<0.05	<0.001	<0.001	0.66	<0.001
	Rotation	2	0.46	0.22	<0.001	0.37	0.56
	Farming system x rotation	6	1	0.70	<0.001	1	1.00
FAST	Farming system	1	<0.001	<0.001	<0.001	<0.001	<0.001
	Tillage	1	<0.001	<0.001	<0.001	<0.001	<0.001
	Cover cropping	3	0.35	<0.001	<0.001	0.52	<0.001
	Farming system x tillage	1	<0.001	<0.001	<0.001	<0.01	<0.001
	Farming system x cover cropping	3	0.95	0.85	<0.001	0.94	0.34
	Tillage x cover cropping	3	0.83	0.97	<0.001	0.79	0.09
	Farming system x tillage x cover cropping	3	0.97	0.93	<0.001	0.96	0.88
Frick	Tillage	1	0.40	0.80	<0.01	0.40	<0.05
	Fertilization	1	<0.05	<0.001	0.13	<0.01	0.15
	Tillage x fertilization	1	0.99	0.89	0.85	0.98	0.86

Table5

Table 5 Greenhouse (GHG) emissions, changes in soil organic C (SOC) content, total N and C inputs and yield calculated for the main treatments at four long-term experimental (LTE) sites over 30 years. Standard errors (SE) were computed by linear mixed effects models in SAS. Positive change in SOC indicates SOC sequestration, while a negative change indicates a decrease in SOC. Positive values of soil CH_4 oxidation refer to CH_4 uptake. Positive values for net soil GHG emissions (NSGHGE) denote net GHG source, while negative values denote a net sink for GHG emissions. GHGI refers to GHG intensity.

LTE	Treatment		N_2O	N inputs*	N_2O proportion**	Δ SOC	C inputs***	CO_2	CH_4 oxidation	NSGHGE	Yield****	GHGI
			kg N ha^{-1} y^{-1} ± SE	kg N ha^{-1} y^{-1} ± SD	%	g C m^{-2} y^{-1} ± SE	g C m^{-2} y^{-1} ± SD	g C m^{-2} y^{-1} ± SE	g CH_4 m^{-2} y^{-1} ± SE	kg CO_2eq ha^{-1} yr^{-1} ± SE	kg ha^{-1} yr^{-1} ± SE	kg CO_2eq kg-^{1} yield ± SE
P29C‡	Clay	CL	2.06 ± 0.08	141.59 ± 29.56	1.45	-19.90 ± 15.83	184 ± 148	730 ± 581	0.148 ± 0.002	1545 ± 594	4365 ± 351	0.35 ± 0.000
		CH	2.09 ± 0.08	141.56 ± 29.57	1.48	-19.21 ± 15.83	180 ± 145	704 ± 581	0.148 ± 0.002	1534 ± 594	4322 ± 351	0.35 ± 0.000
		PL	2.16 ± 0.08	141.53 ± 29.57	1.53	-25.49 ± 15.83	179 ± 144	934 ± 581	0.148 ± 0.002	1792 ± 594	4339 ± 351	0.41 ± 0.000
		RT	1.92 ± 0.08	141.48 ± 29.60	1.36	-12.84 ± 15.83	187 ± 140	471 ± 581	0.147 ± 0.002	1230 ± 594	4385 ± 351	0.28 ± 0.000
	Loam	CL	1.83 ± 0.08	141.50 ± 29.58	1.30	-14.11 ± 15.83	172 ± 138	518 ± 581	0.189 ± 0.002	1228 ± 594	4452 ± 351	0.28 ± 0.000
		CH	1.88 ± 0.08	141.50 ± 29.59	1.33	-14.17 ± 15.83	168 ± 136	520 ± 581	0.190 ± 0.002	1249 ± 594	4402 ± 351	0.28 ± 0.000
		PL	1.91 ± 0.08	141.47 ± 29.59	1.35	-16.86 ± 15.83	168 ± 135	618 ± 581	0.190 ± 0.002	1361 ± 594	4418 ± 351	0.31 ± 0.000
		RT	1.75 ± 0.08	141.41 ± 29.60	1.24	-8.57 ± 15.83	175 ± 131	314 ± 581	0.189 ± 0.002	989 ± 594	4484 ± 351	0.22 ± 0.000
DOK	K1		1.66 ± 0.07	134.50 ± 42.89	1.23	-12.83 ± 7.31	244 ± 223	471 ± 268	0.207 ± 0.003	1103 ± 264	8799 ± 549	0.13 ± 0.001
	K2		2.81 ± 0.07	198.22 ± 70.09	1.42	-6.42 ± 7.31	313 ± 264	235 ± 268	0.205 ± 0.003	1347 ± 264	9907 ± 549	0.14 ± 0.001
	M2		1.95 ±0.07	164.03 ± 47.08	1.19	-17.62 ± 7.31	185 ± 203	646 ± 268	0.208 ± 0.003	1402 ± 264	9169 ± 549	0.15 ± 0.001
	N		0.79 ± 0.07	78.30 ± 49.97	1.01	-24.78 ± 7.31	155 ± 193	908 ± 268	0.205 ± 0.003	1182 ± 264	6049 ± 549	0.20 ± 0.001
	O1		1.27 ± 0.07	112.65 ± 44.10	1.13	-16.20 ± 7.31	236 ± 224	594 ± 268	0.208 ± 0.003	1064 ± 264	7924 ± 549	0.13 ± 0.001
	O2		1.94 ± 0.07	150.46 ± 64.33	1.29	-11.10 ± 7.31	306 ± 266	407 ± 268	0.208 ± 0.003	1156 ± 264	9009 ± 549	0.13 ± 0.001
FAST	CON - IT	CONT	1.36 ± 0.06	131.02 ± 79.25	1.04	-23.98 ± 13.93	191 ± 182	879 ± 511	0.171 ± 0.003	1397 ± 511	5048 ± 465	0.35 ± 0.002
		MUST	1.38 ± 0.06	131.13 ± 79.46	1.05	-21.53 ± 13.93	208 ± 200	789 ± 511	0.176 ± 0.003	1314 ± 511	5255 ± 465	0.31 ± 0.002
		MIX	1.35 ± 0.06	131.35 ± 79.67	1.03	-20.28 ± 13.93	210 ± 204	744 ± 511	0.176 ± 0.003	1258 ± 511	5292 ± 465	0.30 ± 0.002
		VETCH	1.48 ± 0.06	138.03 ± 75.74	1.07	-15.55 ± 13.93	243 ± 252	570 ± 511	0.176 ± 0.003	1136 ± 511	5787 ± 465	0.25 ± 0.002
	CON - NT	CONT	1.05 ± 0.06	131.04 ± 79.91	0.80	-5.75 ±13.93	184 ± 163	211 ± 511	0.214 ± 0.003	590 ± 511	4829 ± 465	0.15 ± 0.002
		MUST	1.07 ± 0.06	131.08 ± 79.96	0.82	-8.74 ± 13.93	197 ± 172	320 ± 511	0.167 ± 0.003	721 ± 511	4832 ± 465	0.19 ± 0.002
		MIX	1.08 ± 0.06	131.03 ± 79.87	0.83	-8.54 ± 13.93	198 ± 173	313 ± 511	0.167 ± 0.003	718 ± 511	4816 ± 465	0.19 ± 0.002
		VETCH	1.17 ± 0.06	138.04 ± 76.43	0.85	-6.20 ± 13.93	217 ± 195	227 ± 511	0.166 ± 0.003	667 ± 511	5087 ± 465	0.16± 0.002
	ORG - IT	CONT	1.40 ± 0.06	135.48 ± 77.25	1.03	-11.67 ± 13.93	237 ± 211	428 ± 511	0.171 ± 0.003	962 ± 511	4344 ± 465	0.28 ±0.002
		MUST	1.45 ± 0.06	134.60 ± 75.70	1.08	-7.72 ± 13.93	260 ± 235	283 ± 511	0.176 ± 0.003	837 ± 511	4694 ± 465	0.22 ±0.002
		MIX	1.45 ± 0.06	134.60 ± 75.66	1.08	-6.56 ± 13.93	265 ± 243	241 ± 511	0.176 ± 0.003	794 ± 511	4700 ± 465	0.21 ±0.002
		VETCH	1.53 ± 0.06	141.32 ± 72.94	1.09	-1.98 ± 13.93	297 ± 291	73± 511	0.177 ± 0.003	662 ± 511	5251 ± 465	0.16 ±0.002
	ORG - RT	CONT	1.31 ± 0.06	130.12 ± 69.07	1.01	24.04 ± 13.93	255 ± 217	-882 ± 511	0.171 ± 0.003	-384 ± 511	3310 ± 465	-0.15 ±0.002
		MUST	1.39 ± 0.06	129.94 ± 68.61	1.07	21.94 ± 13.93	280 ± 239	-805 ± 511	0.176 ± 0.003	-275 ± 511	3450 ± 465	-0.10 ±0.002
		MIX	1.35 ± 0.06	129.98± 68.80	1.04	22.76 ± 13.93	284 ± 246	-834 ± 511	0.175 ± 0.003	-322 ± 511	3497 ± 465	-0.11 ±0.002
		VETCH	1.43 ± 0.06	136.87 ±66.48	1.05	31.13 ± 13.93	328 ± 312	-1142 ± 511	0.175 ± 0.003	-594 ± 511	3939 ± 465	-0.19 ±0.002
Frick	CT	MC	1.86 ± 0.10	107.35 ± 44.21	1.73	-4.36 ± 22.14	206 ± 96	160 ± 812	0.168 ± 0.003	886 ± 797	7142 ± 762	0.12 ± 0.002
		SL	2.14 ± 0.10	110.18 ± 47.16	1.94	-22.05 ± 22.14	191 ± 99	808 ± 812	0.168 ± 0.003	1654 ± 797	7345 ± 762	0.23 ± 0.002

RT	MC	1.86 ± 0.10	105.95 ± 42.11	1.76	1.82 ± 22.14	226 ± 104	-67 ± 812	0.169 ± 0.003	661 ± 797	7428 ± 762	0.09 ± 0.002
	SL	2.16 ± 0.10	108.82 ± 44.33	1.98	-16.12 ± 22.14	209 ± 106	591 ± 812	0.169 ± 0.003	1443 ± 797	7586 ± 762	0.19 ± 0.002

* Total N inputs comprise of organic and mineral fertilizers, biological N fixation, and atmospheric deposition.

** Refers to a proportion of total N inputs lost as soil N_2O emissions.

*** Total C inputs comprise of plant litter (above-, belowground) and organic fertilizers.

**** Yield comprises of harvested grain, tuber, vegetable and forages such as silage maize and grass-clover.

ǂ Due to a lack of plot-specific soil properties, only one simulation was run per treatment at this LTE site.

Table 6 Relative (%) and absolute (kg CO_2eq ha^{-1} or kg CO_2eq kg^{-1}) changes in annual soil GHG emissions in response to studied soil management combinations compared with the baseline treatment in four long-term experiments (LTEs). GHGI refers to GHG intensity. The baseline represented by the treatment with the highest soil GHG emissions on an area basis at each LTE site is denoted by underlining. Mean differences (± standard error) relative to the baseline were calculated as differences of least squares means by linear mixed effects models in SAS.

LTE	Treatment		NSGHGE		CO_2		N_2O		GHGI	
			kg CO_2eq ha^{-1} yr^{-1}	%	kg CO_2eq ha^{-1} yr^{-1}	%	kg CO_2eq ha^{-1} yr^{-1}	%	kg CO_2eq kg^{-1} yield	%
P29C	Clay	PL								
		CH	-258 ± 295	-14	-230 ± 291	-25	-28 ± 12	-3	-0.06 ± 0.000	-14
		CL	-247 ± 295	-14	-205 ± 291	-22	-42 ± 12	-5	-0.06 ± 0.000	-14
		RT	-563±295	-31	-464±291	-50	-99 ± 12	-11	-0.13 ± 0.000	-32
	Loam	PL								
		CH	-112 ± 295	-8	-99 ± 291	-16	-13 ± 12	-2	-0.02 ± 0.000	-8
		CL	-133 ± 295	-10	-101 ± 291	-16	-33 ± 12	-4	-0.03 ± 0.000	-10
		RT	-372 ± 295	-27	-304 ± 291	-49	-68 ± 12	-9	-0.09 ± 0.000	-28
DOK	M2									
	K1		-299 ± 230	-21	-176 ± 237	-27	-124 ± 31	-15	-0.03 ± 0.002	-18
	K2		-55 ± 230	-4	-411 ± 237	-64	355 ± 31	44	-0.02 ± 0.002	-11
	O1		-338 ± 230	-24	-52 ± 237	-8	-286 ± 31	-35	-0.02 ± 0.002	-12
	O2		-246 ± 230	-18	-239 ± 237	-37	-6 ± 31	-1	-0.02 ± 0.002	-16
	N		-220 ± 230	-16	262 ± 237	41	-483 ± 31	-59	0.04 ± 0.002	28
FAST	CON - IT	CONT								
		MUST	-83 ± 275	-6	-90 ± 287	-10	8 ± 24	1	-0.03 ± 0.003	-10
		MIX	-140 ± 275	-10	-136 ± 287	-15	-3 ± 24	0	-0.05 ± 0.003	-14
		VETCH	-261 ± 275	-19	-309 ± 287	-35	49 ± 24	9	-0.10 ± 0.003	-29
	CON - NT	CONT	-807 ± 275	-58	-668 ± 287	-76	-127 ± 24	-22	-0.19 ± 0.003	-56
		MUST	-677 ± 275	-48	-559 ± 287	-64	-119 ± 24	-21	-0.16 ± 0.003	-46
		MIX	-680 ± 275	-49	-566 ± 287	-64	-115 ± 24	-20	-0.16 ± 0.003	-46
		VETCH	-730 ± 275	-52	-652 ± 287	-74	-80 ± 24	-14	-0.18 ± 0.003	-53
	ORG - IT	CONT	-436 ± 275	-31	-451 ± 287	-51	16 ± 24	3	-0.07 ± 0.003	-20
		MUST	-560 ± 275	-40	-596 ± 287	-68	38 ± 24	7	-0.12 ± 0.003	-36
		MIX	-603 ± 275	-43	-639 ± 287	-73	37 ± 24	7	-0.13 ± 0.003	-39
		VETCH	-735 ± 275	-53	-806 ± 287	-92	73 ± 24	13	-0.19 ± 0.003	-54
	ORG - RT	CONT	-1782 ± 275	-128	-1761 ± 287	-200	-21 ± 24	-4	-0.49 ± 0.003	-142
		MUST	-1672 ± 275	-120	-1684 ± 287	-192	13 ± 24	2	-0.45 ± 0.003	-129
		MIX	-1719 ± 275	-123	-1714 ± 287	-195	-4 ± 24	-1	-0.46 ± 0.003	-133
		VETCH	-1991 ± 275	-143	-2021 ± 287	-230	31 ± 24	5	-0.53 ± 0.003	-154
Frick	CT	SL								
		MC	-768 ± 363	-46	-649 ± 373	-80	-119 ± 25	-13	-0.10 ± 0.003	-45
	RT	SL	-211 ± 363	-13	-217 ± 373	-27	7 ± 25	1	-0.03 ± 0.003	-16
		MC	-992 ± 363	-60	-875 ± 373	-108	-117 ± 25	-13	-0.14 ± 0.003	-60

Figure1

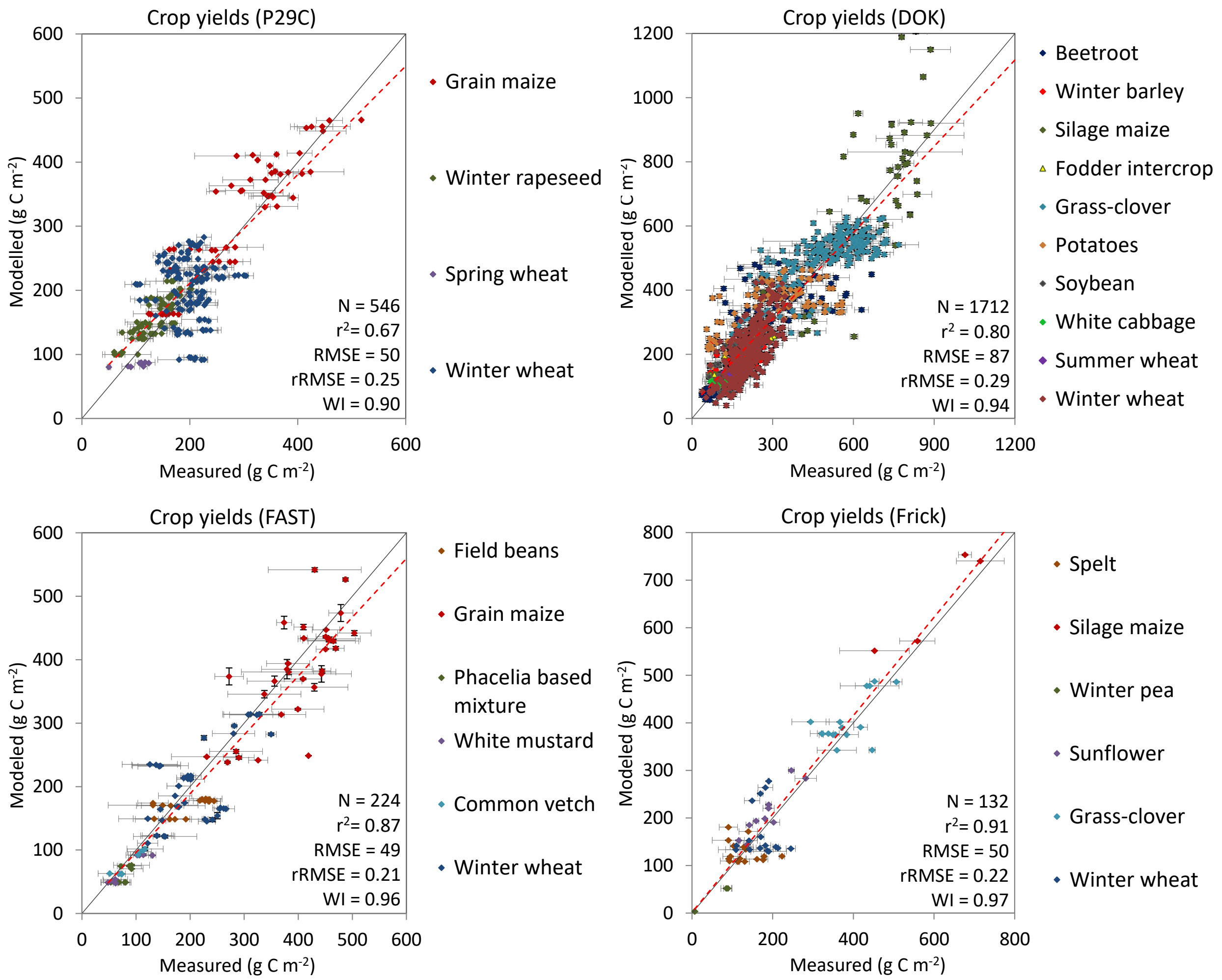
Crop yields (P29C)
Modelled (g C m-2)
Measured (g C m-2)
0
100
200
300
400
500
600
0
200
400
600
N = 546
r2= 0.67
RMSE = 50
rRMSE = 0.25
WI = 0.90
Grain maize
Winter rapeseed
Spring wheat
Winter wheat
Crop yields (DOK)
Modelled (g C m-2)
Measured (g C m-2)
0
200
400
600
800
1000
1200
0
300
600
900
1200
N = 1712
r2 = 0.80
RMSE = 87
rRMSE = 0.29
WI = 0.94
Beetroot
Winter barley
Silage maize
Fodder intercrop
Grass-clover
Potatoes
Soybean
White cabbage
Summer wheat
Winter wheat
Crop yields (FAST)
Modeled (g C m-2)
Measured (g C m-2)
0
100
200
300
400
500
600
0
100
200
300
400
500
600
N = 224
r2= 0.87
RMSE = 49
rRMSE = 0.21
WI = 0.96
Field beans
Grain maize
Phacelia based mixture
White mustard
Common vetch
Winter wheat
Crop yields (Frick)
Modeled (g C m-2)
Measured (g C m-2)
0
100
200
300
400
500
600
700
800
0
200
400
600
800
N = 132
r2= 0.91
RMSE = 50
rRMSE = 0.22
WI = 0.97
Spelt
Silage maize
Winter pea
Sunflower
Grass-clover
Winter wheat

Figure2

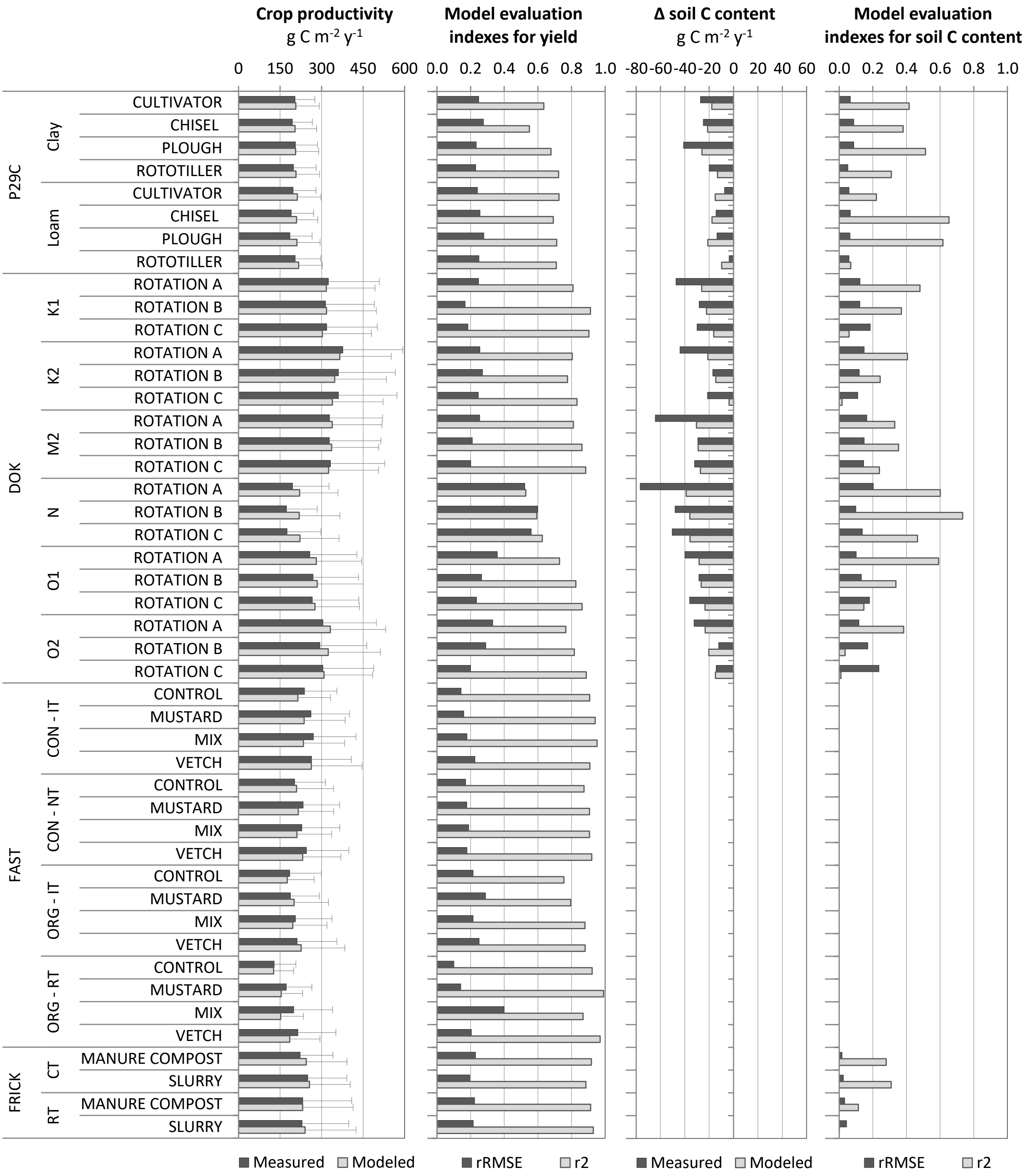
Crop productivity
g C m-2 y-1
Model evaluation
indexes for yield
Δ soil C content
g C m-2 y-1
Model evaluation
indexes for soil C content
0 150 300 450 600
0.0 0.2 0.4 0.6 0.8 1.0
-80 -60 -40 -20 0 20 40 60
0.0 0.2 0.4 0.6 0.8 1.0
P29C
Clay
CULTIVATOR
CHISEL
PLOUGH
ROTOTILLER
Loam
CULTIVATOR
CHISEL
PLOUGH
ROTOTILLER
DOK
K1
ROTATION A
ROTATION B
ROTATION C
K2
ROTATION A
ROTATION B
ROTATION C
M2
ROTATION A
ROTATION B
ROTATION C
N
ROTATION A
ROTATION B
ROTATION C
O1
ROTATION A
ROTATION B
ROTATION C
O2
ROTATION A
ROTATION B
ROTATION C
FAST
CON - IT
CONTROL
MUSTARD
MIX
VETCH
CON - NT
CONTROL
MUSTARD
MIX
VETCH
ORG - IT
CONTROL
MUSTARD
MIX
VETCH
ORG - RT
CONTROL
MUSTARD
MIX
VETCH
FRICK
CT
MANURE COMPOST
SLURRY
RT
MANURE COMPOST
SLURRY
■ Measured ▨ Modeled
■ rRMSE ▨ r2
■ Measured ▨ Modeled
■ rRMSE ▨ r2

Figure3

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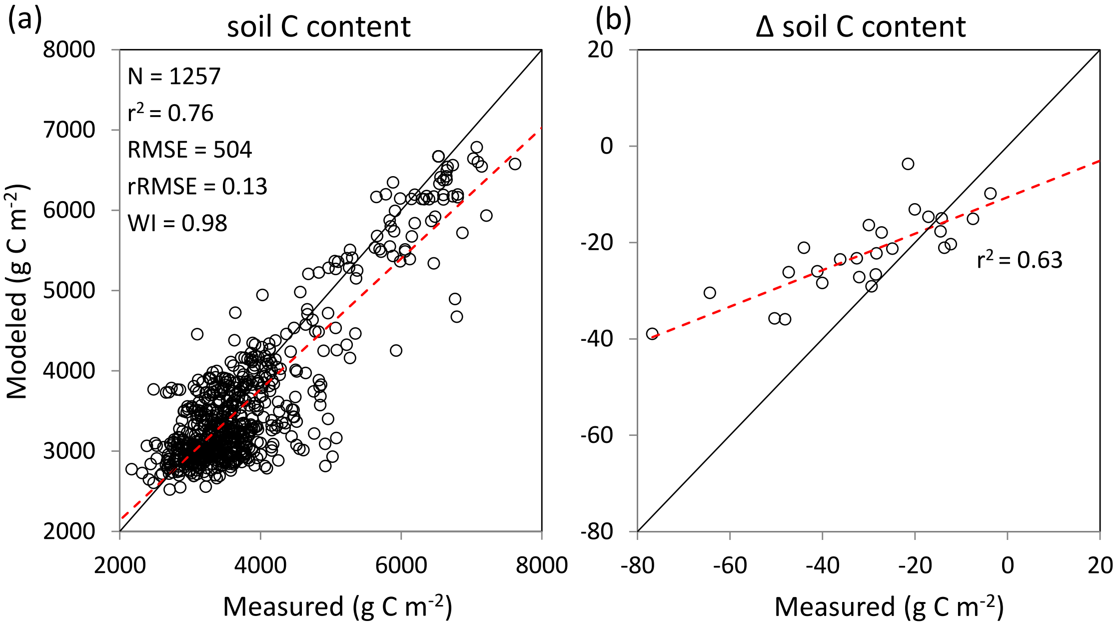

Figure4

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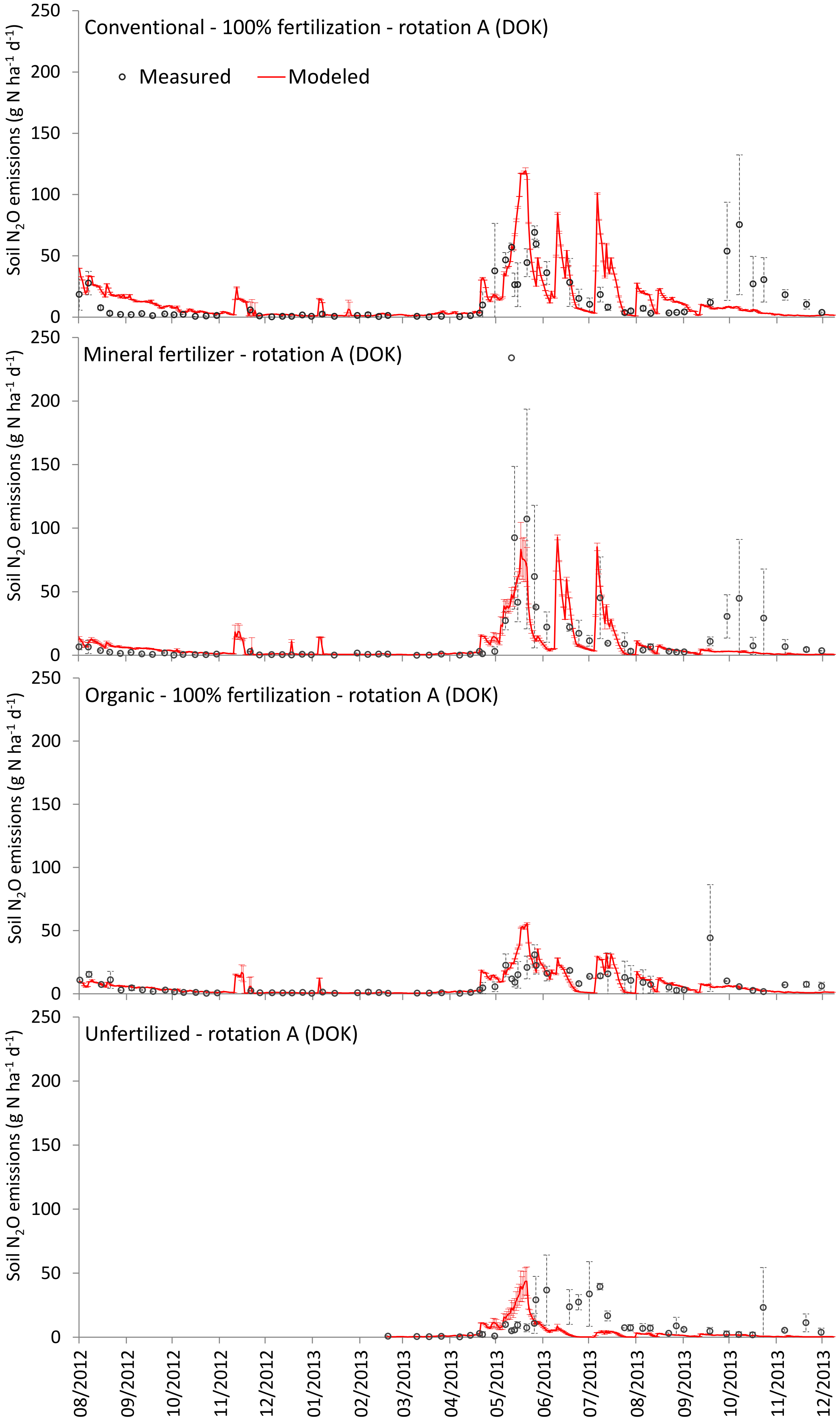
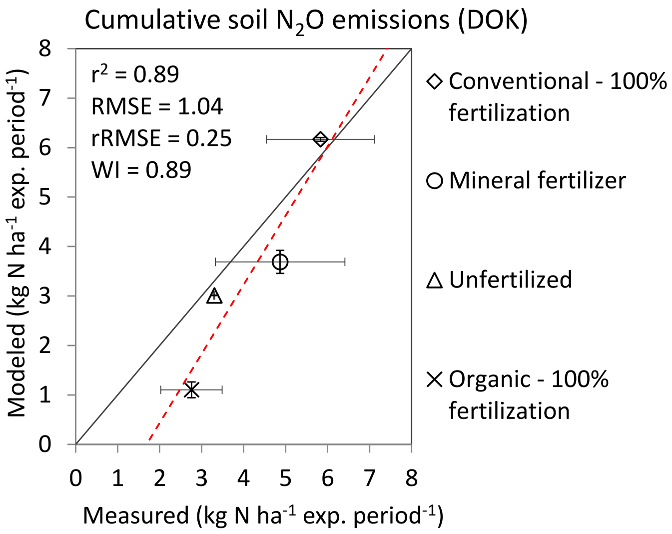



Cumulative soil N_2O emissions (DOK)
r^2 = 0.89
RMSE = 1.04
rRMSE = 0.25
WI = 0.89
Modeled (kg N ha^{-1} exp. $period^{-1}$)
Measured (kg N ha^{-1} exp. $period^{-1}$)
0
1
2
3
4
5
6
7
8
◇ Conventional - 100% fertilization
○ Mineral fertilizer
△ Unfertilized
× Organic - 100% fertilization

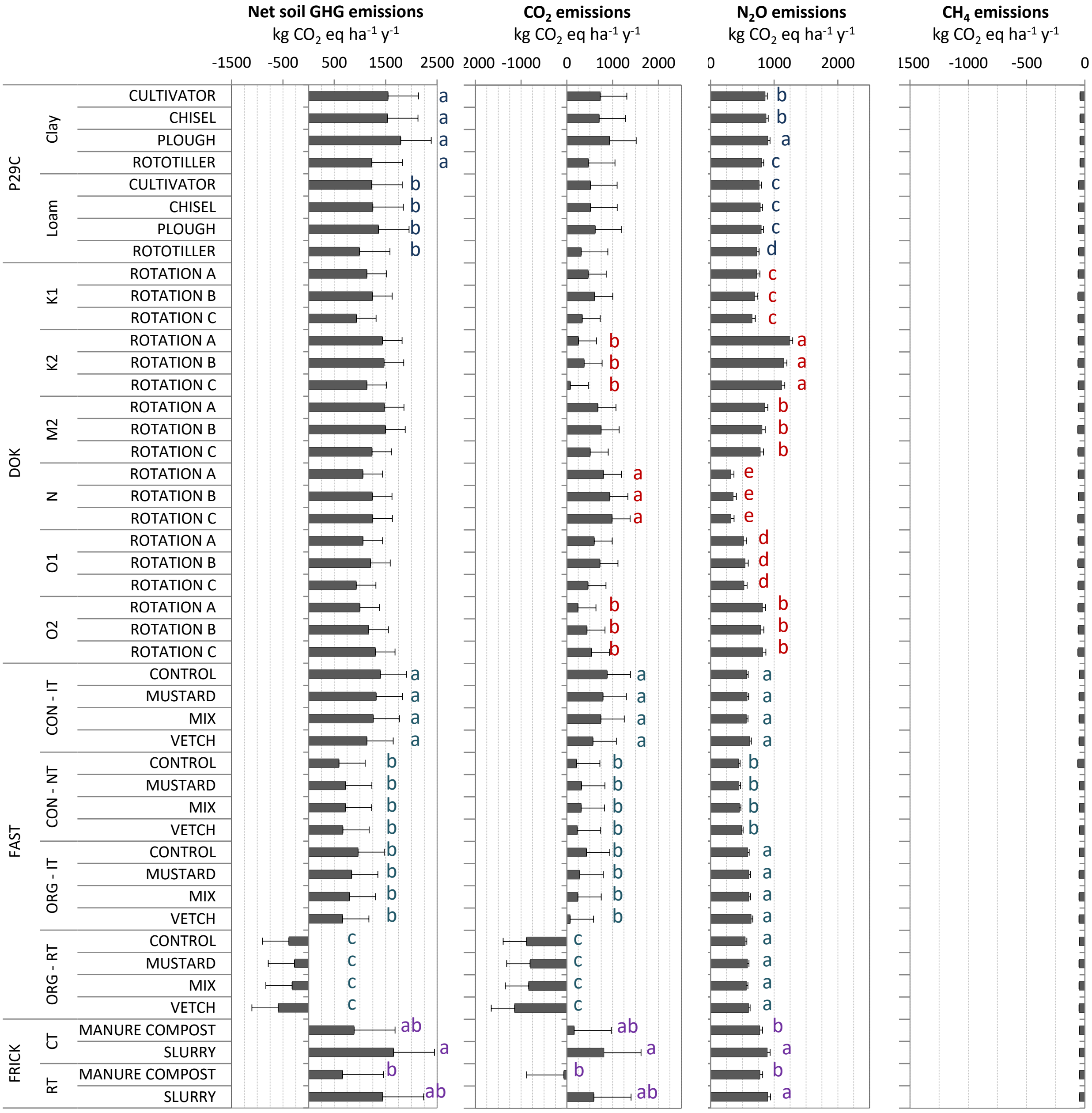

Net soil GHG emissions
kg CO$_2$ eq ha^{-1} y^{-1}
-1500 -500 500 1500 2500
CO$_2$ emissions
kg CO$_2$ eq ha^{-1} y^{-1}
-2000 -1000 0 1000 2000
N$_2$O emissions
kg CO$_2$ eq ha^{-1} y^{-1}
0 1000 2000
CH$_4$ emissions
kg CO$_2$ eq ha^{-1} y^{-1}
-1500 -1000 -500 0
P29C
Clay
CULTIVATOR
CHISEL
PLOUGH
ROTOTILLER
Loam
CULTIVATOR
CHISEL
PLOUGH
ROTOTILLER
DOK
K1
K2
M2
N
O1
O2
ROTATION A
ROTATION B
ROTATION C
FAST
CON - IT
CON - NT
ORG - IT
ORG - RT
CONTROL
MUSTARD
MIX
VETCH
FRICK
CT
RT
MANURE COMPOST
SLURRY
a
b
c
d
e
ab

Figure B.1

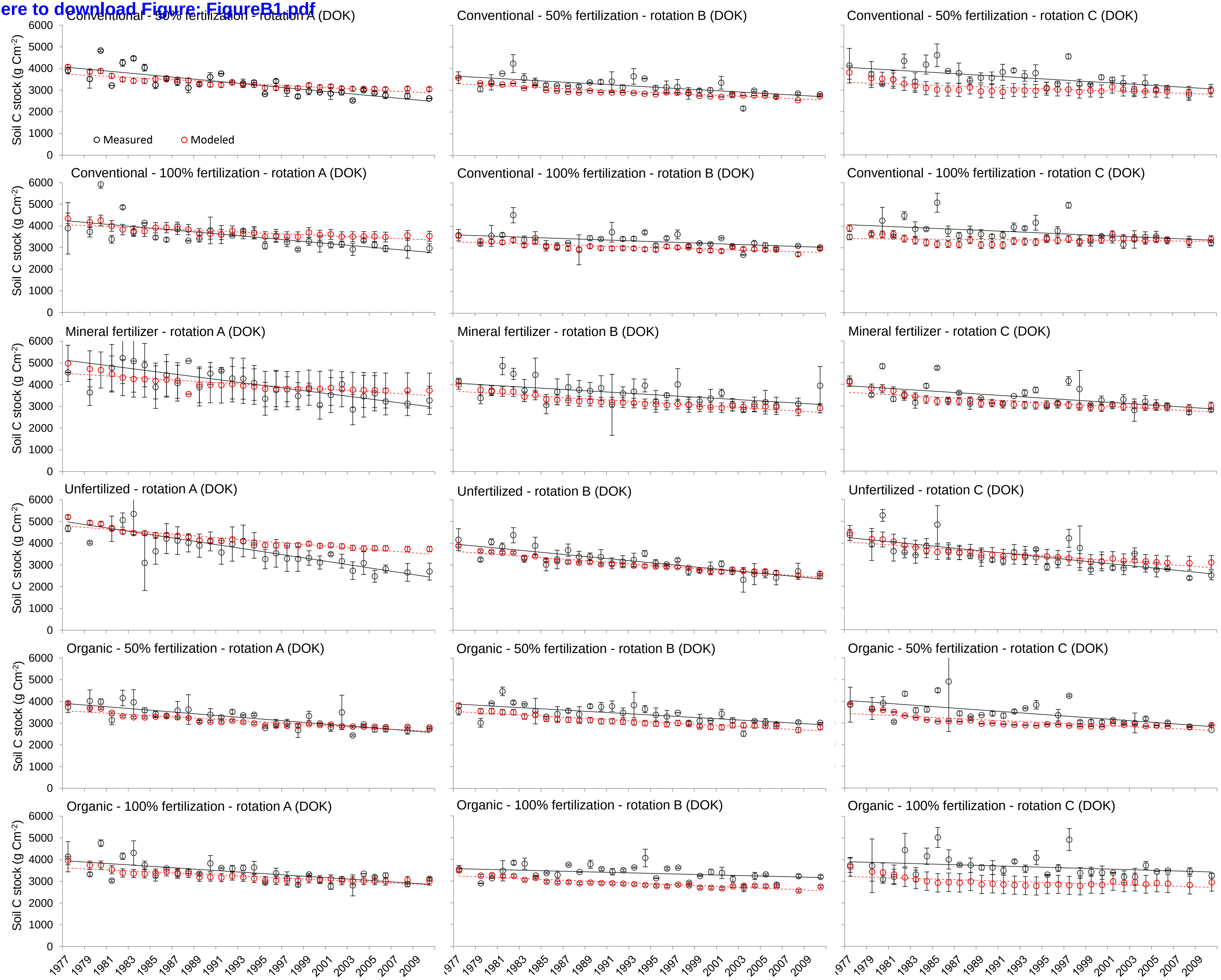
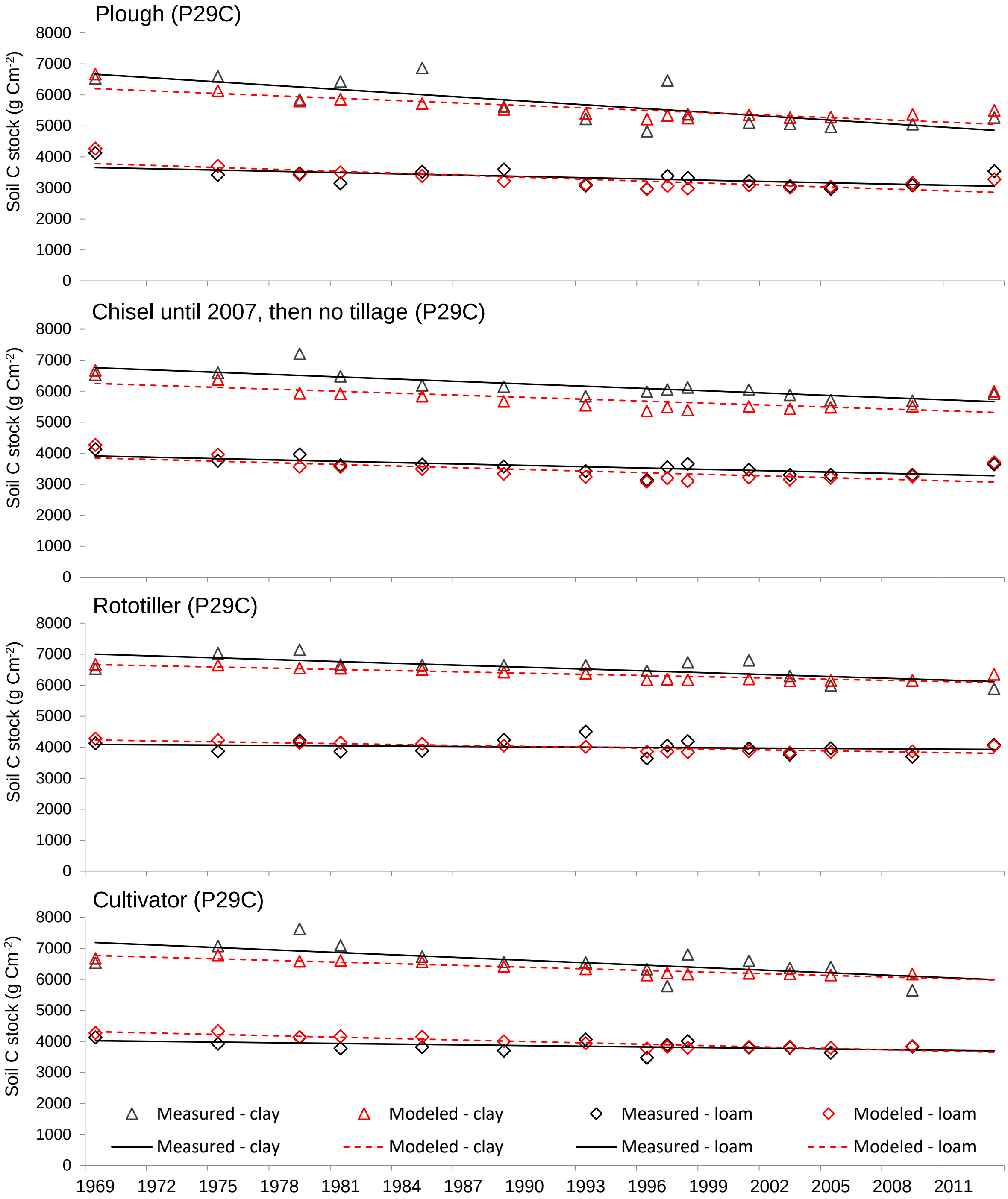
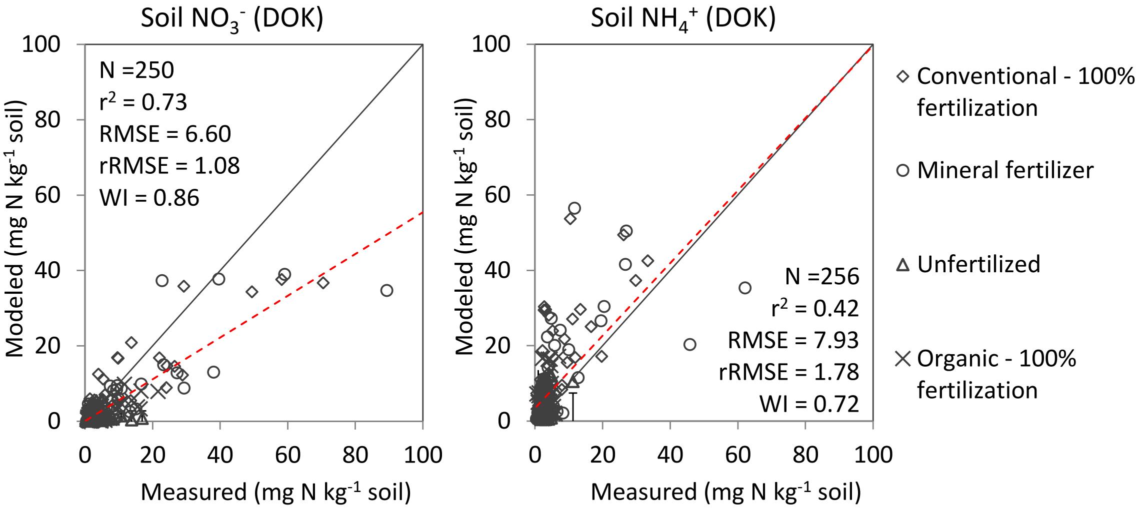

Conventional - 50% fertilization - rotation A (DOK)
Conventional - 50% fertilization - rotation B (DOK)
Conventional - 50% fertilization - rotation C (DOK)
Conventional - 100% fertilization - rotation A (DOK)
Conventional - 100% fertilization - rotation B (DOK)
Conventional - 100% fertilization - rotation C (DOK)
Mineral fertilizer - rotation A (DOK)
Mineral fertilizer - rotation B (DOK)
Mineral fertilizer - rotation C (DOK)
Unfertilized - rotation A (DOK)
Unfertilized - rotation B (DOK)
Unfertilized - rotation C (DOK)
Organic - 50% fertilization - rotation A (DOK)
Organic - 50% fertilization - rotation B (DOK)
Organic - 50% fertilization - rotation C (DOK)
Organic - 100% fertilization - rotation A (DOK)
Organic - 100% fertilization - rotation B (DOK)
Organic - 100% fertilization - rotation C (DOK)
Soil C stock (g Cm⁻²)
6000
5000
4000
3000
2000
1000
0
○ Measured
○ Modeled
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009

Figure B.2


Plough (P29C)
Chisel until 2007, then no tillage (P29C)
Rototiller (P29C)
Cultivator (P29C)
Soil C stock (g Cm-2)
0
1000
2000
3000
4000
5000
6000
7000
8000
1969
1972
1975
1978
1981
1984
1987
1990
1993
1996
1999
2002
2005
2008
2011
△ Measured - clay
△ Modeled - clay
◇ Measured - loam
◇ Modeled - loam
— Measured - clay
- - - Modeled - clay
— Measured - loam
- - - Modeled - loam


Soil NO3- (DOK)
N =250
r2 = 0.73
RMSE = 6.60
rRMSE = 1.08
WI = 0.86
Modeled (mg N kg-1 soil)
Measured (mg N kg-1 soil)
0
20
40
60
80
100
Soil NH4+ (DOK)
N =256
r2 = 0.42
RMSE = 7.93
rRMSE = 1.78
WI = 0.72
Modeled (mg N kg-1 soil)
Measured (mg N kg-1 soil)
◇ Conventional - 100% fertilization
○ Mineral fertilizer
△ Unfertilized
× Organic - 100% fertilization