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Simulating soil carbon sequestration from long term fertilizer and manure additions under continuous wheat using the DailyDayCent model

K. Begum · M. Kuhnert · J. Yeluripati · M. Glendining · P. Smith

Abstract The widely used ecosystem model DailyDayCent (DDC) was used to predict soil organic carbon (SOC) sequestration and yield under different fertilization treatments on a wheat (*Triticum aestivum*) monoculture on Broadbalk field, Rothamsted, UK. Over a period of about 170 years, the management practices on the test site, which is separated into plots with different treatments of fertilizer and manure application, are well documented. Four treatments consisting of control (no fertilizer), mineral nitrogen (N) fertilizer (MN), farm yard manure (FYM) and a combination of both (FYMN) have been selected for the study. DDC simulated the greatest increases in SOC (three times higher compared to simulation of the control plot) in the FYM plot. Overall a good agreement between modelled and measured yield was obtained (except in control plots). As observed in the experimental plots, the highest yield predicted by the model is with FYMN plot (more than three times higher relative to the control plot). A sensitivity test for the MN and FYM plots demonstrated that predicted SOC was relatively insensitive (1%) to bulk density, pH and field capacity. Higher sensitivity (4–7%) of predicted SOC changes were observed by changes in external C input. An increase of temperature by 1 °C or precipitation by 10% decreased predicted SOC by 2–4% and vice versa, and simulated a 1–4% variability in yield. DDC is a useful tool for simulating SOC in the long term plots, with a good fit to data, and is useful for examining alternate hypotheses of yield and SOC responses.

Keywords Long term experiments · Modelling · SOC · Fertilization · Sensitivity

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Introduction

Soil organic matter (SOM) is an important component in terrestrial ecosystems. Beside its significant role in nutrient availability, soil resilience, water holding capacity and crop productivity (Lal 2013; Smith et al. 1996), SOM plays a key role in mitigating climate change by capturing atmospheric carbon dioxide (CO_2), an important radiatively active gas emitted mainly by anthropogenic activities (Alexander et al. 2015; Smith et al. 1996). It is estimated that close to

90% of the total mitigation potential in the agricultural sector could be derived from soil organic carbon (SOC) sequestration, with about 10% from reduction of non-CO_2 greenhouse gases (Smith et al. 2007). Several mitigation options have been suggested for croplands, as reviewed in Intergovernmental Panel on Climate Change, IPCC (Smith et al. 2007, 2014) e.g., nutrient management, tillage and residue management, and water management. As a consequence, article 3.4 of the Kyoto Protocol includes agricultural management practices as a potential carbon (C) sink to mitigate climate change impact (Smith 2004), and many Nationally Determined Contributions submitted by parties to the United Nations Framework Convention on Climate Change, as part of the Paris Climate Agreement, also include soil C sequestration.

Changes in SOC content can be very slow; sometimes taking more than 100 years to reach a new equilibrium, depending on the type of management practices and soil type (Smith et al. 1996). Therefore, existing long-term datasets may be the best options to assess whether current agronomic practices are sustaining agricultural and environmental quality. The complexity of soil C dynamics, and slow changes of SOC, mean that computer models are a powerful option for simulating and predicting SOC change in different fertilization experiments over long time scales (Powlson 1996). The Broadbalk winter wheat experiment at Rothamsted is the oldest continuing agronomic field experiment in the world (Rothamsted Research 2006). To predict SOC dynamics, the RothC model was tested at this site (Jenkinson et al. 1990). Powlson et al. (2012) recently presented SOC changes with RothC at this site, and Falloon and Smith (2000) studied SOM turnover using RothC and CENTURY. The above literature, however, is restricted to the investigation of SOC changes only. Several studies have been published on testing the impact of different fertilization regimes on yield at Broadbalk and observed weather has direct (Chmielewski and Potts 1995) or indirect impact (Thorne et al. 1988) on yield variability. Recently, Powlson et al. (2014) investigated the reason for comparatively lower yield in continuous wheat section relative to wheat rotation, and found impacts of 'adverse' weather, which sometimes leads to very late sowing due to saturation of the soil when the original planting time was planned, or susceptibility to disease of the wheat variety used.

SOC changes and yield have been studied separately in a few previous studies, but they have not been evaluated together. To support holistic policy, tools that allow soil C change and yield to be considered together are needed. The performance of ecosystem models that can determine the impact of the different processes on soil C dynamics and plant production using available data is therefore critical. The current study aimed to predict SOC sequestration and yield under long term fertilization treatments at the Broadbalk continuous wheat experiment using the widely used ecosystem model DailyDayCent (DDC). DDC has recently been used to simulate nitrous oxide fluxes from wheat cropland in the UK (Fitton et al. 2014) and from a corn-wheat-barley rotation in France (Senapati et al. 2016). The magnitude of SOC sequestration depends on a number of factors including variables describing weather, soil properties, management and external nutrient input. A sensitivity analysis was used to detect the most sensitive parameters, which is crucial for a better understanding of the processes and aspects of the model structure critical in simulating yield and SOC change. A better understanding of the parameter sensitivity will also improve the analysis for future model experiments.

Methods

Site description

The study uses data from the Broadbalk continuous wheat experiment, situated at Rothamsted Research, Harpenden, Herts UK (0°22′W and 51°49′N, 128 m above sea level). Initially the experiment was set up to test the effects of various combinations of fertilizers on crop yield, but over time the experiment has been modified, to ensure that it remains relevant to current agricultural issues, whilst retaining its long-term integrity (Macdonald et al. 2015). The fertilizer treatments varied at the initiation of the experiment, but in 1852 a scheme was established which has continued, with some modifications, to the present day. Originally, the treatments were applied to single plots, about 320 m (m) long and 6 m wide (Moss et al. 2004). In 1926 the field was sub-divided into five sections, crossing the treatment strips, which were sequentially fallowed to control weeds. In 1968 the experiment was further divided into 10 sections, so

Table 1 Different nitrogen fertilizer and manure treatments applied to the plots selected for the current study

Name of the plot	Treatment
Control	No fertilizer or manure since 1843
MN	144 kg N ha^{-1} a^{-1} since 1843[a]
FYM	35 t ha^{-1} a^{-1} FYM since 1843[b]
FYMN	35 t ha^{-1} a^{-1} FYM since 1885[b];
	Plus 96 and 144 kg N ha^{-1} added along with FYM since 1968 and 2005, respectively

[a] For this study this treatment is considered as N fertilizer only, the plot has also received non-limiting P, K, Mg and Na since 1843

[b] C content in FYM (farmyard manure) estimated as 3 t ha^{-1}, total N content estimated before 1968 as 224 kg N ha^{-1} (Johnston and Garner 1969) and measured thereafter between 158 and 322 kg N ha^{-1}

that the yield of continuous wheat could be compared with wheat grown in rotation. Modern, short-straw cultivars were introduced. The plots are now approximately 25 m long and 6 m wide (Moss et al. 2004). The management practices on the test site are well documented.

The present study uses data from Section one, where winter wheat has been grown continuously since 1843, with occasional fallow years to control weeds, the last in 1966. The crop is sown in the autumn (usually September–October) and harvested in the summer (usually August) of the following year. The soil is clay loam (Soil Survey of England and Wales classification, Avery 1980), alkaline in nature (pH between 7.1 and 8.2). The average temperature is 9 °C, and the average annual precipitation is about 700 mm. In order to test the optimum yield, the management practices have been changed from time to time. Weed control was one of the major concerns on the site and weeds were removed manually until 1926, then by sequential fallowing, 1 year in five from 1926 to 1966. Herbicides were introduced to control weeds in 1964 (Moss et al. 2004). The combination of modern higher yielding varieties, better weed control, liming and the use of fungicides increased yields by 2–3 times in all fertilized treatments.

The straw is removed at harvest in this section, and we assume residue incorporation of 38% of total above-ground residue (consisting of stubble and chaff and uncollected straw) for the control treatment, and 30% for the other fertilized treatments in this continuous wheat section as suggested by previous literature (Powlson et al. 1986). For more details of the site and the treatments see http://www.era.rothamsted.ac.uk/Broadbalk.

In order to estimate the SOC trend by the model simulations in this study, four plots were selected with different fertilization treatments. Beside a no fertilizer or manure plot (Control), three plots with different nutrient applications were considered: mineral nitrogen (N) fertilizer (MN), farm yard manure (FYM) and combined application of mineral N and manure (FYMN). All details are summarized in Table 1.

SOC data

There are 11–14 measurements of SOC between 1843 and 2014, measured at irregular intervals (5–25 years). The initial SOC content for all plots in 1843 was estimated to be 1% in the top 0.23 m. SOC stock (t ha^{-1}) at 0.23 m depth was obtained from e-RA, the electronic Rothamsted Archive e-RA (http://www.era.rothamsted.ac.uk/Broadbalk/bbk_open_access). SOC (t ha^{-1}) was estimated from measured %SOC, standard soil weights, and adjustment for changes in bulk density (BD) in the FYM and FYMN treatments. As the model provides SOC outputs for 0.20 m depth, the modelled SOC was recalculated for a 0.23 m depth based on the assumption of an equal distribution of SOC in the top layer, so modelled values were divided by 0.87.

Yield data

Grain and straw yield data were obtained from e-RA (http://www.era.rothamsted.ac.uk/). We used annual grain yields from 1852 to 2014 for the four treatments indicated in Table 1 (1885–2014 for FYMN). There were 10 fallow years (no yield) between 1926 and 1966, so a total of 153 years of data (120 years for FYMN). Actual agronomic data (sowing and harvest dates, dates of fertilizer and manure application etc.) were also provided in the data base. Nitrogen content

data of the FYM applied was available from 1968 onwards; before that date total N content was estimated (Table 1).

Model description and initialization

DDC (version from 1st of May 2013) was derived from the model CENTURY (Parton et al. 1998) and DayCent (Del Grosso et al. 2001, 2012). The DDC includes a daily plant production sub-model at a daily time step. This modification allows DDC to produce daily plant production outputs like net primary productivity, net ecosystem exchange and heterotrophic respiration which are directly comparable with daily eddy covariance measurements, whereas DayCent model version computes these variables on a weekly basis. DDC simulates the biogeochemical processes of C, N, phosphorus, and sulphur cycling associated with SOM dynamics for grasslands, agricultural lands, forests, and savannas. The minimum weather data used to run the model are precipitation, maximum and minimum temperature at daily time steps. Required input data include (1) soil data such as soil texture, soil depth, BD, water characteristics like field capacity (FC), hydraulic conductivity and water filled pore space for each depth specified by the model (2) agronomic information of the test sites, such as sowing date, harvesting date, ploughing events (date and procedure), fertilization events (date, kind and amount of fertilizer), irrigation events (date and amount) and residue removal, and (3) phenological parameters and plant specific constants describing the growth potential and sensitivity to drought or nutrient stress (Del Grosso et al. 2012).

Sub-models in DDC determine soil organic matter (SOM) decomposition, nitrification and denitrification, plant production and soil water dynamics. Figure 1a represents the plant production sub model. In the plant production sub model, the assimilated C is allocated to aboveground and belowground biomass pools by allocation factors which are affected by nutrient and water stress. C from plant residues and animal manure is subdivided into structural and metabolic pools on the basis of lignin fraction (Fig. 1b). The metabolic pool contains readily decomposable materials (turn-over time 0.1–1 year), whereas the structural pool contains plant lignin that is resistant to decomposition (turn-over time 1–5 year). The SOM sub model transfers C to three SOC pools, namely active (turn-over time 1–5 year), slow (turn-over time 20–50 years) and passive pools (turn-over time 200–1500 years), where the turnover of C in different pools is described by a first order kinetic considering decomposition rate, soil texture, soil temperature, moisture, tillage and lignin/N ratio (Parton 1996).

The overall set up for the simulations to establish initial steady state conditions for the different SOC pools at the start of the experiment are: (1) initialization starts with grass for 1500 years followed by arable cropping of a further 350 years (as the literature suggested; Avery and Bullock 1969; Rothamsted Research 2006), with the minimum inorganic fertilizer (50 kg N ha^{-1}) application and keeping minimum residues (1%) left in the field, (2) the simulation followed the actual management practices since 1843, the beginning of the experiment (details were described in Table 1). Annual inputs are roots, roots exudates, stubble and part of the chaff (estimated by Jenkinson et al. 1992). In the model the belowground biomass is simulated and dead roots contribute to the carbon pools, (3) to better reflect improved cultivars and thereby represent the higher yield observed since 1968, we adjusted the plant production parameter in the DDC crop file, and the value remained fixed during 1968–2014. No irrigation is applied to the Broadbalk experiment.

Statistical methods

Performance of the DDC model was tested using the model evaluation statistical routines provided in MODEVAL (as suggested by Smith et al. 1997; Smith and Smith 2007). We compared the measured and modelled SOC and yield by calculating root mean square error (RMSE), mean error (E), mean difference between observation and simulation (M), and sample correlation coefficient (r), shown below as Eqs. 1, 2, 3 and 4, respectively:

$$RMSE = \frac{100}{\bar{O}} \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{1}$$

$$E = \frac{100}{\bar{O}} \frac{\sum_{i=1}^{n}(O_i - P_i)}{n} \tag{2}$$

$$M = \frac{\sum_{i=1}^{n}(O_i - P_i)}{n} \tag{3}$$

Fig. 1 Schematic structure of **a** the plant production sub-model and **b** the SOC sub-model in DDC (Adapted from Parton and Rasmussen 1994; Paustian et al. 1997)
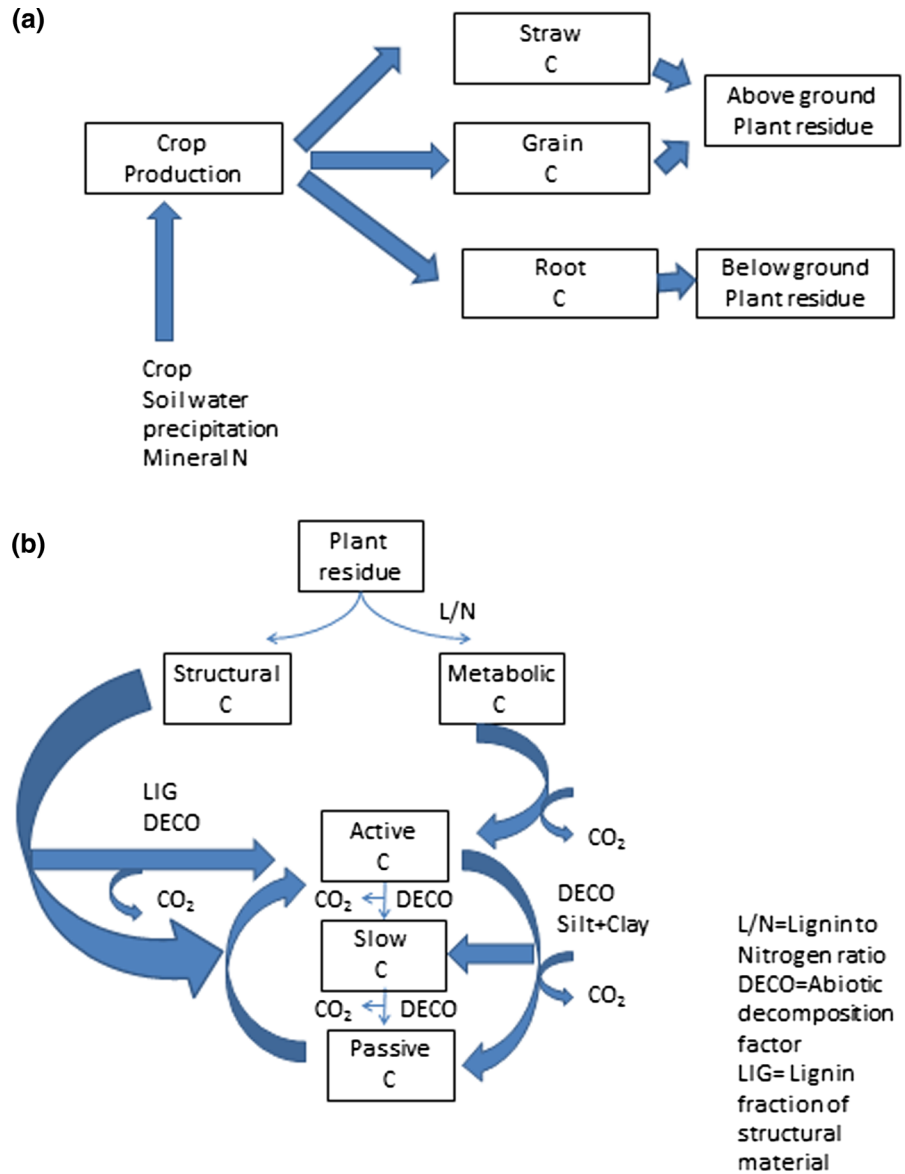
$$r = \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\left[\sum_{i=1}^{n}(O_i - \bar{O})^2\right]}\sqrt{\left[\sum_{i=1}^{n}(P_i - \bar{P})^2\right]}} \quad (4)$$

where $\bar{O}$ and $\bar{P}$ is the mean values of observed and predicted data and O_i and P_i indicate the observed and predicted values, respectively, and n is the number of measurements. The significance of r and M was tested using an F-test (at probability levels of $p = 0.05$, $p = 0.01$ and $p = 0.001$), and Student's two-tailed t test (critical at 2.5%), respectively.

Sensitivity test

The sensitivity of the simulated SOC and yield towards several input parameters were tested by the modification of 10 parameters (one parameter at a time) including 2 climatic parameters (daily temperature and precipitation), 4 soil parameters (FC, BD, pH and clay content), initial SOC content, and 3 additional management inputs (residue return, N content of fertilizer in MN plot and C content of the FYM in FYM plot). Based on the assessment of Senapati et al.

(2016), the range used in this study were considered as daily air temperature modified by $\pm$ 1 °C, pH by $\pm$ 1 unit, and the other parameters by $\pm$ 10% of the measured values (baseline values). For each simulation, only a single input was varied and all other parameters remained the same as in baseline level. The simulated final SOC in response to a change of individual parameters for the period of 1843–2014 was deducted from the final simulation with baseline SOC for the same period, and the percentage change in SOC due to change in each input was determined. Average values for the period 1968–2014 were calculated to assess sensitivity of yield to different parameters.

Results

SOC and yield simulation

The modelled SOC showed a good fit with the measured data (Fig. 2), which is supported by a low values (RMSE < 10%) in the error analysis (Table 2).

SOC in the control plot shows a slight negative trend at the end of the period which is reflected in the modelled results (r = 0.54), with slight underestimation (E = 1%) but no bias. There is a small systematic bias (slight overestimation, E = − 5%) in the MN plot, and the positive relationship (r = 0.48) between modelled and measured SOC is not significant. Modelled SOC in the FYM and FYMN plots shows a highly significant agreement (p = < 0.001) with the measurements. The decrease of SOC at the end of the simulations tends to underestimate SOC in FYM plot, but with no significant bias. As seen in the measurements, the maximum SOC was simulated for the FYM plot, more than three times greater than the control plot, and two times greater than the MN plot. The second highest impact was observed by application of N and manure (FYMN plot, started in 1885). Simulated output and measured SOC increased rapidly over the first 80 years, after which SOC increase rate slowed.

The modelled yield in general shows a good fit with the measured data (RMSE < 45%) except for simulation of the control plot, which is underestimated by 70% or 0.66 t ha^{-1} (Fig. 3 and Table 2). The yield under different fertilization shows a highly significant positive relationship (p < 0.001). The highest yield was seen in the FYMN plot, with an average of 6 t ha^{-1} for the period of 1968–2014, which was well

matched by the model (Fig. 3). The average observed and modelled yield for the MN and FYMN plots are the same, at around 5 t ha^{-1}. A systematic bias (overestimation by less than 1 t ha^{-1}) was observed in the MN and FYMN plots.

Sensitivity analysis

Sensitivity of simulated SOC to the tested parameters on both plots showed that the maximum change in SOC over 170 years was about 8% different from baseline inputs, and the impact appeared to be lower due to changes in soil properties (FC, BD and soil pH) observed in both plots (Table 3). Changes of N content in mineral fertilizers has negligible impact on SOC increase, as observed in the MN plot, whereas changes of C content in manure by 10% lead to changes in SOC by 4–7%, with the maximum impact obtained in the FYM plot among the selected parameters. Increasing air temperature by 1 °C tends to decrease SOC by 2–4%, while SOC increases by 3–5% with decreasing temperature. There was a 3–4% change in SOC when precipitation was modified by 10%. Yield changed by a maximum of 8% on modification of the selected parameters. Yield is less responsive to changes of temperature by 1 °C than SOC and the response was lower (1%) in the MN plot than the plot with FYM application. Yield declined by 1–2% on the MN plot when increasing or decreasing precipitation by 10%. Increased precipitation increase yield by 3% on the FYM plot, while yield decreased by 4% on lowering precipitation on this plot. Yield changes of around 8% under modification of FC indicates that the model is sensitive to these parameters. A yield decline of 3–4% occurred under an increase of clay content by 10% and vice versa. A 10% decrease of N content in chemical fertilizer reduced yield by 5%, and a 6% higher yield was obtained when the C content in manure was increased by 10% compared to the current practice. As for the SOC content, BD and pH had a negligible impact (0.02–2%) on yield over the 170 years.

Discussion

Modelled SOC and yield

Testing the DDC model for its ability to simulate SOC indicates a good agreement between modelled and
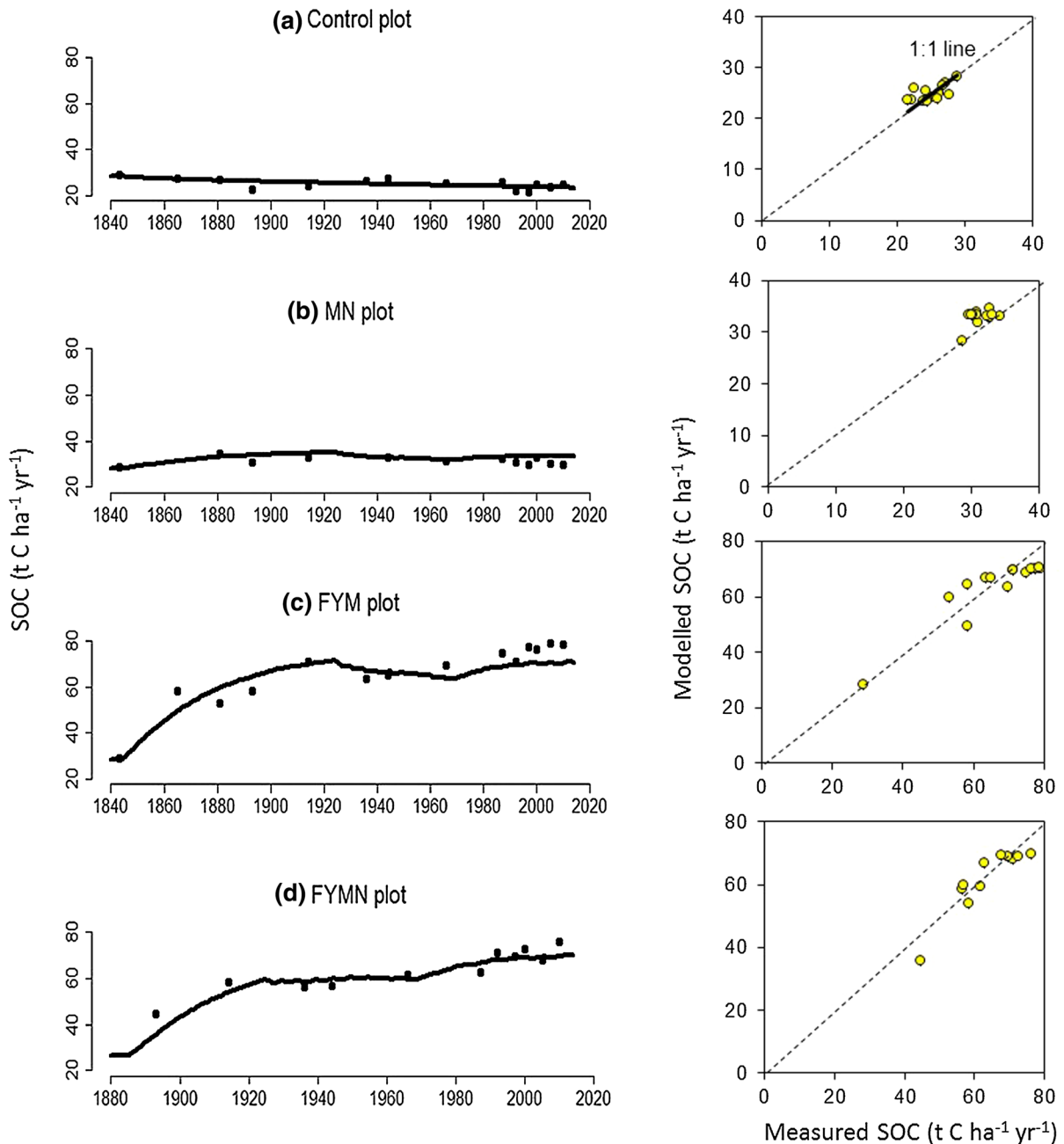
Fig. 2 Measured (points) and modelled (line) SOC for the different treatments (0–0.23 m depth) in the long term Broadbalk continuous wheat test site for the period 1843–2014 (the FYMN treatment started in 1885): **a** control plot **b** MN plot, **c** FYM plot and **d** FYMN plot

measured values on the considered sites over the studied period. As seen in the measurements, lower SOC contents were simulated in the control plot, since inputs of C were lowest on this low yielding plot. On the MN plot, SOC increased by 20% more than in the

control plot, due to residue C input (Glendining et al. 1996). The uptake of C by grain and straw at harvest simulated by DDC is 3.53 t C ha^{-1} a^{-1} for the period 1970–1985, which is close to the value of 3.51 t C ha^{-1} a^{-1} estimated by Jenkinson et al.

Table 2 Statistical output for modelled and measured SOC (1843–2014) and yield (1852–2014) under different fertilization treatment from the Broadbalk continuous wheat experiment

	Control (n1 = 14[a] n2 = 153[b])	MN (n1 = 12 n2 = 153)	FYM (n1 = 14 n2 = 153)	FYMN (n1 = 11 n2 = 120)
SOC				
RMSE (%)	6.59	7.12	8.88	6.65
E (%)	1.06	− 5.01	3.88	2.74
M (t ha^{-1})	0.08^{ns}	− 1.57*	2.56^{ns}	1.69^{ns}
r	0.61*	0.48^{ns}	0.87***	0.92***
Yield				
RMSE (%)	83.35	41.72	38.00	32.01
E (%)	71.17	− 2.62	− 4.21	− 6.55
M (t ha^{-1})	0.66*	− 0.08*	− 0.16^{ns}	− 0.23*
r	− 0.24**	0.79***	0.75***	0.68***

ns non-significant

[a] n1 = number of samples of measured SOC

[b] n2 = number of samples of measured yield

* Significant correlation (r) between modelled and measured at $p < 0.05$, or significant mean error (M) at $p = 0.025$

** Significant correlation (r) between modelled and measured at $p < 0.01$

*** Significant correlation (r) between modelled and measured at $p < 0.001$

(1992) for the MN plot. DDC estimates C input in the MN plot quite well. However, a slight over prediction of SOC at the end of simulation was observed. The greater C input due to higher yield tends to accumulate more C in the soil, thereby leading to an over prediction of SOC in the MN plot. As for the measurements, a sharp increase in SOC occurred in the middle years of the simulations of the manured plot, which was attributed to accumulation of more C in SOC slow pool. In the FYMN plot, direct C addition by manure and residue input outweighed the soil respiration over the study period. In contrast to the observations, a slower SOC increase was simulated in the FYM plot, which suggests that the reduced manure-only applications during the fallow period could not compensate for the C lost by respiration.

Overall, a good agreement was observed between modelled and measured yield, except for the plot with no nutrient input (control plot). In spite of no fertilizer application, a yield increase in the control plot has been observed (Clark et al. 2012; Powlson et al. 2014), which, it has been proposed, could be due to atmospheric N deposition of around 35–45 kg N ha^{-1} a^{-1}. Including N deposition in

DDC tends to reduce the gap between modelled and measured yield, but could not explain the entire gap between modelled results and observations. DDC was originally developed for grasslands (Parton et al. 1987) and croplands where there is usually an external N source, and biogeochemical models are known to simulate low input regimes less well (Senapati et al. 2016). It could also be that the model does not simulate enough mineralization of organic matter to release N for use by the crops.

Sensitivity analysis

The sensitivity test revealed that SOC at the Broadbalk site was less sensitive to changes of soil BD and FC by 10% and pH by 1 unit. Since BD cannot be altered during model simulations, for the FYM and FYMN plots we used the initial soil weight value of 2.88×10^6 kg ha^{-1} at 0–0.23 m as estimated in 1843 for the duration of the simulations, though soil weight is known to have decreased over time to 2.52×10^6 kg ha^{-1} at 0–0.23 m measured in 2000. However, our sensitivity analysis has shown that SOC change is relatively insensitive to changes in BD, with
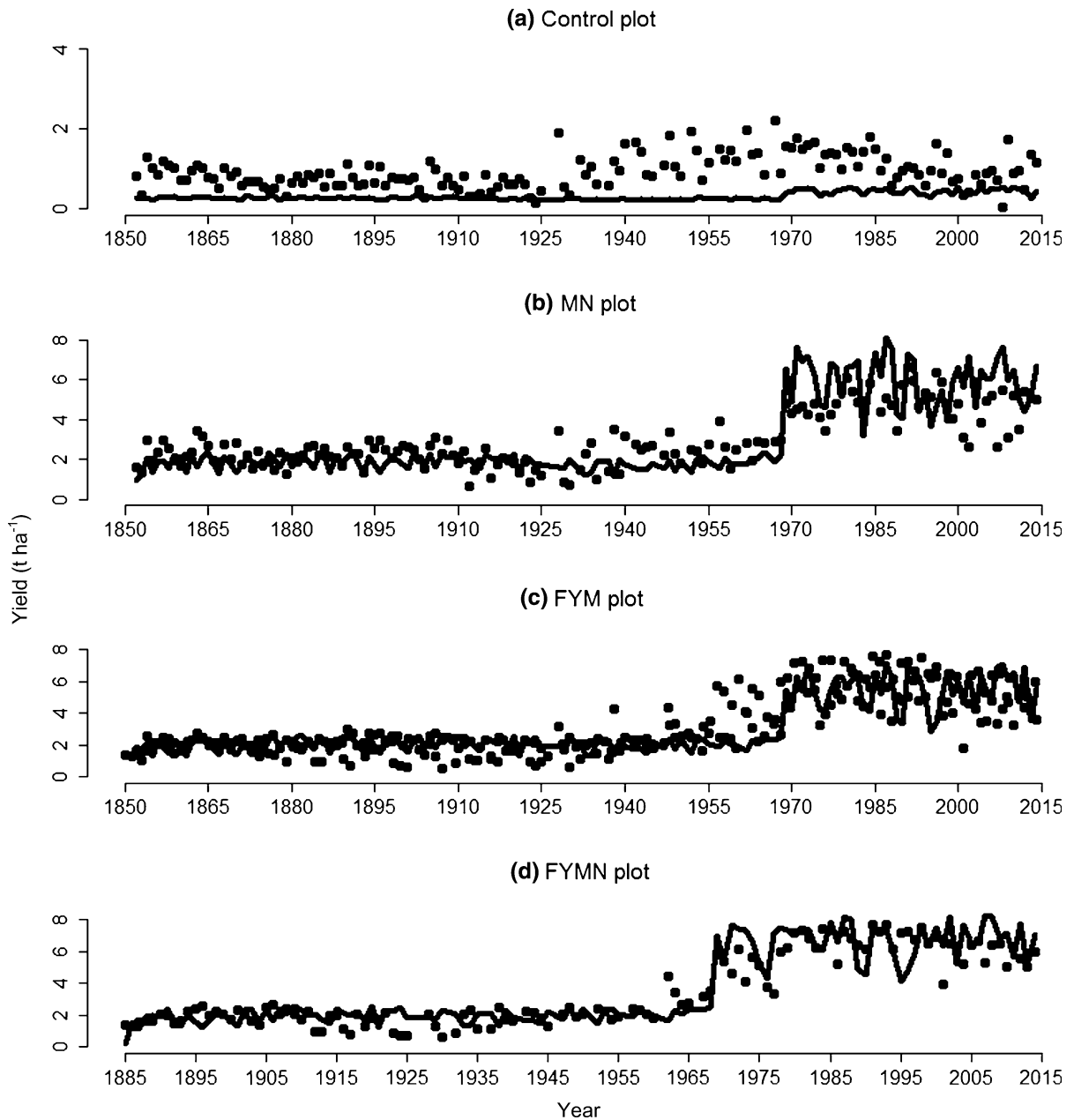
Fig. 3 Modelled (line) and measured (point) yield under four treatments in the Broadbalk continuous winter wheat experiment test site for the period of 1852–2014 (FYMN treatment started in 1885). **a** Control plot, **b** MN plot, **c** FYM plot and **d** FYMN plot. Note that the y-axis scale range for **a** is 0–4 t ha^{-1} while for the other treatment 0–8 t ha^{-1}

a 10% decrease in BD leading to only a 0.28% decrease in SOC, so using a fixed BD value would not have greatly affected the simulation outcomes. Similarly, lime has been applied in some plots to keep pH between 6.5 and 8.2 on this site. We tested the sensitivity to pH, and the model experiment revealed that SOC is relatively insensitive to a change in pH by one unit, which may be too small to impact on plant production or microbial activity. An additional model experiment of reducing pH by 2 units shows an increase in the SOC pool by 5% and an 8% increase in yield compared to the original simulations. It should

Table 3 Sensitivity of modelled SOC (1843–2014) and yield (1968–2014) to climatic parameters, soil properties, model variables and management input on MN and FYM plot

Simulated variables	Parameter	Range	MN plot % change	FYM plot % change
SOC				
	Daily air temperature	± 1 °C	− 2.15/2.56	− 4.24/5.03
	Daily precipitation	± 10%	− 3.15/4.47	− 3.13/4.19
	FC	± 10%	0.65/− 0.94	− 0.21/− 0.16
	BD	± 10%	− 0.1/0.1	0.16/− 0.28
	pH	± 1	− 0.26/0.75	− 0.10/1.2
	Clay content	± 10%	− 1.06/2.71	− 1.39/2.58
	Initial SOC	± 10%	6.33/− 7.95	3.07/− 3.84
	Residue return	± 10%	6.66/− 6.48	3.77/− 3.66
	N content in fertilizer	± 10%	0.23/− 0.66	
	C content in manure	± 10%		4.0/− 7.25
Yield				
	Daily air temperature	± 1 °C	− 1.06/− 0.98	− 2.20/2.46
	Daily precipitation	± 10%	− 1.15/− 1.92	2.67/− 4.26
	FC	± 10%	6.69/− 7.75	6.58/− 7.58
	BD	± 10%	− 0.14/− 0.13	2.03/− 2.38
	pH	± 1	− 0.10/0.23	− 0.02/1.64
	Clay content	± 10%	− 3.43/4.65	−3.56/3.77
	Initial SOC	± 10%	0.06/− 0.07	0.07/− 0.08
	Residue return	± 10%	0.86/− 0.89	2.12/− 2.15
	N content in fertilizer	± 10%	1.64/− 5.01	
	C content in manure	± 10%		5.88/− 4.81

be noted, however, that reduced pH will have other, detrimental effects on the soil, which will have an effect on crop growth. Decreasing clay content increases simulated SOC and plant production. The sensitivity tests of modified C applications show that external C input is one of the most important factors affecting SOC change that is reflected in both the MN and the FYM plots. Addition of 10% more residue increased C input to the soil and so enhanced SOC. SOC increased further when manure was applied, as observed in the FYM plot. Our findings are in line with Oliveira et al. (2017) who predicted the impact of SOC changes under different external C sources using the DayCent model on a Brazilian sugarcane crop. Their study suggests that the negative impact of SOC due to residue removal (75%) can be compensated for by manure application. Although a 10% increase of initial SOC tends to increase SOC, the effect was greater in the MN plot than the plot with FYM applications, but the trend of SOC change was the same as with baseline initial SOC content. This suggests that in terms of SOC change, the impact of initial SOC is negligible. Model

results suggest that changes in rainfall of only 10% on this site do not change the soil water status.

Among the three fertilization practices, FYM sequestered the most C but FYMN gave the best crop yield. The FYMN treatment has had smaller organic inputs than the FYM treatment, as the applications of manure started in 1885, 42 years later than the FYM treatment (see Table 1). Based on SOC sequestration and plant growth, the plot with FYMN shows the highest rates of SOC gain. SOC sequestration through this management is estimated to be around 0.3 t C ha^{-1} a^{-1} over a 130 year period, which is at the top end of the range reported by Smith et al. (2008) for SOC sequestration potential for cool moist croplands (0.002–0.30 t C ha^{-1} a^{-1}). To put this rate of soil carbon sequestration in context, practicing such management on all arable land in the UK would lead to SOC sequestration of ∼ 2 Teragram (Tg) C a^{-1} which is about 1.8% of UK's CO_2-C emissions of 110 Tg C a^{-1} in 2015 (BEIS 2015). However in reality it might not be possible, because increase of SOC by manure addition to one field could result in a

decrease of SOC in other locations due to less manure being applied there (depending on whether or not the manure was used optimally; Smith et al. 2000). SOC sequestration by manure depends on its applicability and availability. FYM produced in the UK amounted to 35.7 Tg in 2010 (Smith and Williams 2016), so only around 16% of total arable land could be covered with manure applied at a rate of 35 t ha^{-1} a^{-1} which would lead to an SOC increase of 0.30 Tg C a^{-1}. If this manure is already being applied to soils, there would be no net gain at the country level.

DDC has a low sensitivity of SOC changes to modification of pH by one unit, and BD, clay content and FC by 10% which suggests that model predictions are not sensitive to any small input uncertainties at this site. DDC is a powerful tool for examining alternate hypothesis of discrepancies between modelled and measured values. The simulation results show consistently good fit to the measurements over the different treatments, which means the model is suitable to test different mitigation options for test sites.

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