A systems model describing the impact of organic resource use on farming households in low to middle income countries

Jo Smith[a,*], Dali Nayak[a], Ashim Datta[b], Wasudeo Nivrutti Narkhede[c], Fabrizio Albanito[a], Bedru Balana[d], Sanjoy Bandyopadhyay[e], Helaina Black[f], Shiferaw Boke[g], Alison Brand[a], Anja Byg[h], Mengistu Dinato[i], Mulugeta Habte[g], Paul D. Hallett[a], Thomas Lemma[i], Wolde Mekuria[j], Awdenegest Moges[i], Alemayehu Muluneh[i], Paula Novo[k], Mike Rivington[l], Tewodros Tefera[i], May Vanni[m], Getahun Yakob[g], Euan Phimister[m]

[a] School of Biological Science, University of Aberdeen, Aberdeen, UK

[b] Division of Soil and Crop Management, ICAR-Central Soil Salinity Research Institute, Karnal-132001, Haryana, India

[c] Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani-431402, Maharashtra, India

[d] International Water Management Institute, Accra Ghana; current address - International Food Policy Research Institute (IFPRI), Abuja, Nigeria.

[e] Indian Agricultural Research Institute, PUSA, New Delhi-110012

[f] Ecological Sciences, James Hutton Institute, Aberdeen, UK

[g] Department of Natural Resources, Southern Agricultural Research Institute, Hawassa, Ethiopia

[h] Social, Economic and Geographical Science Group, James Hutton Institute, Aberdeen, UK

[i] Environment, Gender & Development Studies, Hawassa University, Hawassa, Ethiopia

[j] International Water Management Institute, Addis Ababa, Ethiopia

[k] Land Economy, Environment & Society, Scotland's Rural College (SRUC), Edinburgh, UK

[l] Information and Computational Sciences, James Hutton Institute, Aberdeen, UK

[m] Business School, University of Aberdeen, Aberdeen, UK

[*] Corresponding author: School of Biological Science, University of Aberdeen, Aberdeen, AB24 3UU, UK; Tel: +44 1224272702; Fax: +44 1224272703; Email: jo.smith@abdn.ac.uk

Declaration of interests: None

ABSTRACT

We present a new systems model that encompasses both environmental and socioeconomic outcomes to simulate impacts of organic resource use on livelihoods of smallholder farmers in low to middle income countries. It includes impacts on soils, which in many countries are degrading with long term loss of organic matter. Many farmers have easy access to animal manures that could be used to increase soil organic matter, but this precious resource is often diverted to other purposes, such as fuels, also resulting in loss of the nutrients needed for crop production. This model simulates impacts of different management options on soil organic matter turnover, availability of water and nutrients, crop and animal production, water and energy use, labour requirements and household income and expenditure. An evaluation and example application from India are presented and used to illustrate the importance of considering the whole farm system when developing recommendations to help farmers improve their soils.

Keywords

Whole farm system modelling; organic resource use; farm livelihoods, nitrogen use efficiency; soil water; carbon sequestration

Software availability

The ORATOR model is written in Microsoft Excel to increase transparency (size 6.5 MB). It can be made available, on request, for genuine collaborative work. More information available from Jo Smith, School of Biological Science, University of Aberdeen, Aberdeen, UK, tel: +44 (0)1224 272702, fax: +44 (0)1224 272703, email: jo.smith@abdn.ac.uk.

Abbreviations

BIO = soil biomass

C = carbon

CO_2 = carbon dioxide

DPM = decomposable plant material

EC = electrical conductivity

HUM = soil humus

INR = Indian Rupees

IOM = inert soil organic matter

LPG = liquefied petroleum gas

N = nitrogen

RPM = resistant plant material

SOC = soil organic carbon

1. Introduction

The organic matter content of soils in many low to middle income countries is decreasing, causing long term degradation of the global soil resource (Smith et al., 2016). Soil organic matter is essential for crop production; it supports root growth, improves soil structure, retains water and provides nutrients to the crops (Celestina et al., 2019; Chen et al., 2018; Loveland and Webb, 2003; Murphy, 2015). The amount of organic matter held in the soil is a balance between the inputs and losses; it can be increased by increasing organic inputs or by reducing losses (Smith et al., 2016). Increased inputs can be achieved by incorporating organic manures (Ren et al., 2018; Zavattaro et al., 2017) or crop residues (Ruis and Blanco-Canqui, 2017), by growing crops for soil incorporation (green manures / cover crops) (Ruis and Blanco-Canqui, 2017), by increasing the production of the crops themselves (Rao et al., 2017), or by planting agroforestry systems (Shrestha et al., 2018). Losses can be decreased by protecting soils from high temperatures and heavy rainfall to reduce decomposition and runoff (Prosdocimi et al., 2016; Scopel et al., 2013), by using soil and water conservation measures to reduce erosion (Guerra et al., 2017; Haregeweyn et al., 2015; Li, 2000), or by reducing disturbance of the soils, such as by reduced tillage (Wolka et al., 2018).

Although management practices needed to decrease soil organic matter degradation are well-known, soils continue to degrade (FAO, 2015; UNCCD 2016, 2019). There are perceived or actual costs associated with improved management through organic matter incorporation, the construction of soil water conservation structures or changes to soil cultivation (De Barros et al., 2017). A resource conflict occurs between increased application of organic manures to soils and the amount of manure available for other important purposes, such as for use as household fuels (Smith et al., 2015). Installing soil water conservation structures requires significant labour and uses part of the land area available to grow crops (Gedefaw et al., 2018). Altering soil management to reduced tillage to decrease soil organic matter mineralisation can result in decreased yields due to weeds or soil compaction (Adimassu et al., 2019). In resource limited households, these perceived or actual costs may prevent farmers from following recommendations to improve their soils (Iiyama et al., 2018). In order to reduce soil degradation, recommendations provided to farmers should aim for a more comprehensive account of costs relevant to the household and ensure that the quantifiable benefits demonstrably outweigh any costs; this is what the systems model presented here attempts to do.

While many models exist that consider the different parts of the system individually, models that account for all management decisions taken by a farming household, including biophysical, agricultural and socioeconomic aspects, are lacking. Holzworth et al. (2015) charted the expansion of crop models into agricultural production systems models that provide information on climate change and adaptation, food security, policy assessment and applications, management impacts, resource use and efficiency, plant breeding, bioenergy, livestock and mixed crop-livestock systems, and yield gap analysis. This has involved the development of a number of modelling frameworks that link together multiple and often complex modules from different authors to describe many components of the farming system; these include the Australian APSIM initiative (www.apsim.info), the European projects, SEAMLESS (van Ittersum et al., 2008) and MACSUR (www.macsur.eu), the International Food Policy Research Institute system, DSSAT, which can be linked to the IMPACT model to provide policy analysis (www.dssat.net), and the Global Environment Facility Soil Organic Carbon (GEFSOC) project, which focusses on changes in soil organic matter (e.g. Bhattacharyya et al., 2007). These systems remain focussed on crop and livestock production, and do not yet fully account for the trade-offs between household level food, energy and water provision that occur in low to middle income countries, tending to lack interlinkages between household decision making and cross sector consequences (Matthews et al. (2013). Bakhshianlamouki et al. (2020) presented a model that describes the interlinkages between the water, food and energy sectors and the trade-offs between natural resource use and socio-economic interests associated with lake basin restoration, but this focussed on water balance and the electricity sector, while agricultural benefits used only simplistic representations of net economic benefit and did not consider the underlying processes affecting food production. This missing link between specific farm household management of soils, crops and livestock, and the impacts on food production, energy provision, water use, labour and income is the basis of the new model presented in this paper.

The model is a comprehensive, systems model, aiming to quantify the costs and benefits to low income farmers of implementing measures to reduce loss of soil organic matter. The model accounts for crop and animal production, household energy and water use, on-farm and off-farm labour, and changes in household revenue. The simulations aim to confer improved understanding of the costs and benefits to the household over different timescales, in terms of both labour and finances of different approaches to reducing soil organic matter degradation. From this, it is intended that economically attractive recommendations that also increase the organic matter content of the soil can be developed for rural households, so increasing the likelihood that they will be adopted by farmers.

The model uses generic and easily parameterised components, that include simple but complete descriptions of the underlying processes controlling changes in household resource use. Therefore, it should be easily transferrable to a wide range of different environments and different management practices. Here we describe the model structure and demonstrate its overall functionality for predicting impacts of different management measures on soil organic matter degradation, specifically focussing on the use of inorganic and organic fertilisers. This is done using data for evaluation from a semi-arid site in Maharashtra, India. The measurements at this site provide a rare opportunity to evaluate the model against data from a well-controlled long-term experiment in a semi-arid environment.

2. Materials and methods

2.1. Model overview

The model, known by the acronym ORATOR, “Operational Research Assessment Tool for Organic Resources”, is designed to account for the impact of different uses of farm resources on soil organic matter (section 2.2), crop production (section 2.3), animal production (section 2.4), water use (section 2.5), fuel availability (section 2.6), on- and off-farm labour (section 2.7), and farm income and expenditure (section 2.8) (Fig. 1). It is designed to be quick and simple to use, only requiring input data that are readily available on-farm, but also achieving predictions that are sufficiently accurate to robustly demonstrate options for improved resource use. Different inputs of organic resources to the soil affect resource use in the whole system. Increased inputs of carbon (C) to the soil lead to increases in the soil organic matter, which impacts the water holding capacity and nutrients available to the crop. This affects crop production, which has an impact on animal production using on-farm feeds. The water holding capacity of the soil and growth of crops and animals all affect the requirement for water. Crop production determines the amount of crop residues available to feed to animals and for use as a fuel, and so determines fuel availability (both as crop residues and as dung) and the labour required to collect additional fuel (such as wood). Water use, crops grown and the animals on the farm also impact labour used in farming operations. This then affects labour and time available for off-farm activities. The income and expenditure of the farm are a function of the purchases made by the household (e.g. food, feed, fuel & fertilisers) and the labour and products available within the household (e.g. grain, milk & animals for sale).

The soil component of the model is the most detailed, providing a dynamic simulation of the changes in soil organic matter, water and nutrients (only nitrogen (N) described here) on a monthly time-step. It uses a “pool” type approach, as described by Smith et al. (2010), and follows approaches used in RothC (Coleman and Jenkinson, 1996) and ECOSSE (Smith et al., 2010). The change in crop production is estimated using annual relationships, driven by climatic and nutrient conditions (Leith, 1972; Reid, 2002; Zaks et al., 2007). This is subdivided into monthly values to allow monthly plant inputs to the soil to be calculated. Change in animal production is estimated using production data tables for the chosen region, adjusted according to change in crop production. Available energy, water, labour and finances are then estimated using standard accounting methods.

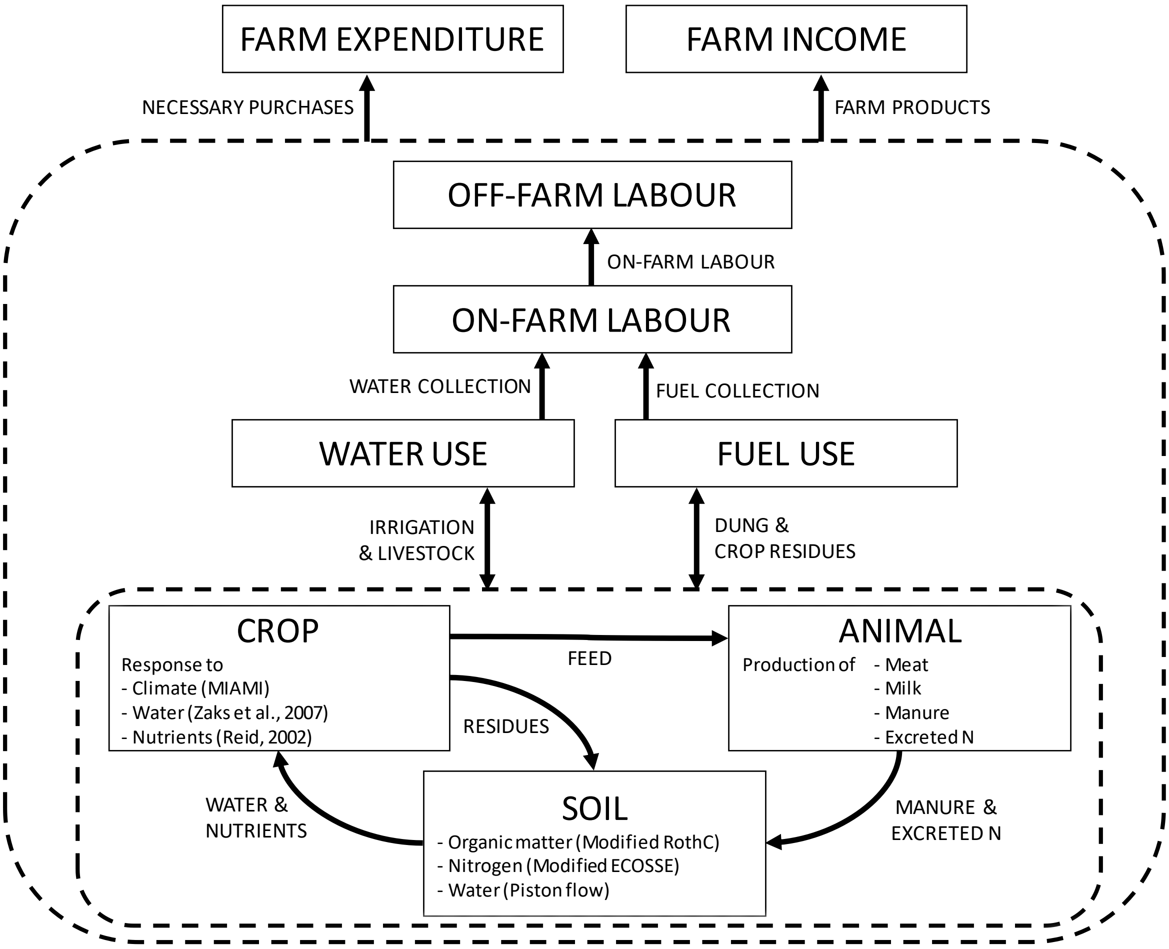


Fig. 1. General structure of the ORATOR model. Direction of arrows indicates the factor affected by the factor(s) at the start of the arrow.

2.2. Soil processes

2.2.1. Soil organic matter

The simulation of changes in soil organic matter are based on the description of aerobic decomposition given by the RothC model (Coleman and Jenkinson, 1996), modified to account for conditions typical of low input agriculture (Table 1). Decomposition is currently only described under aerobic conditions, which will be the most likely decomposition pathway in the system being studied here; anaerobic decomposition is typically much slower than aerobic decomposition, but is important for estimation of greenhouse gas emissions in wet conditions, such as paddy rice, so will be described in later papers. The model is a simple five-pool model that represents soil organic matter as decomposable plant material (DPM), resistant plant material (RPM), actively decomposing “biomass” (BIO), slowly decomposing “humus” (HUM) and inert organic matter (IOM). The model runs on a monthly time-step. Plant material enters the soil as DPM and RPM, in proportions dependent on the land-use type (Coleman and Jenkinson, 1996). The quality of different types of organic waste is described by the proportion of DPM and HUM (Smith et al., 2014). The DPM and RPM decompose to produce BIO, HUM and carbon dioxide (CO_2), in proportions dependent on the clay content of the soil (Coleman and Jenkinson, 1996). The BIO and HUM pools then further decompose to produce more BIO, HUM and CO_2 using the same proportions as for DPM and RPM decomposition. The rate of decomposition is simulated using first order equations, with the rate constants modified by air temperature and soil moisture as described by Coleman and Jenkinson (1996), and by soil acidity as described by Parton et al. (1996) and salinity as described by Setia et al. (2012).

ORATOR uses the assumption of approximate steady state to estimate the activity of the organic matter and the size of plant and organic waste inputs to the soil. The different proportions of the soil organic C (SOC) pools and their respective decomposition rate constants provide a representation of the overall decomposability of SOC. In a soil where SOC is at steady state, the relative proportions of the SOC pools can be determined by running the model until no further changes in SOC content are observed (steady state), adjusting the plant inputs according to the ratio of measured to simulated SOC, re-running to steady state, and continuing this process until the simulated SOC content matches the measured values (Smith et al., 2005). This then allows the impact of changes in land-use, weather and management on SOC turnover to be simulated by running the model forward from steady state with any changes to the steady state conditions imposed (e.g. Smith et al., 1997). Using local measurements or soil database values of SOC to determine SOC pools and plant inputs in this way increases the accuracy with which the model can simulate SOC turnover for a wide range of conditions around the world.

Table 1

Simulation of soil organic matter turnover. Note, C = carbon; DPM = decomposable plant material; RPM = resistant plant material; BIO = rapidly decomposing organic matter, "biomass"; HUM = slowly decomposing organic matter, "humus"; IOM = inert organic matter. Input data are shown in shaded cells.

Symbol	Variable	Value, source or formula	Units	Reference
Carbon content of soil pools, $C_{\mathrm{pool,t}}$				
$C_{\mathrm{pool,t}}$	Amount of C in the pool at time t	$C_{\mathrm{pool,t-1}} + C_{\mathrm{in}} - C_{\mathrm{loss}}$	t ha^{-1}	(1)
$C_{\mathrm{pool,t-1}}$	Amount of C in the pool in the last time-step	From initialisation at steady state and any changes occurring in previous time-steps	t ha^{-1}	(2)
Carbon loss, C_{loss}				
C_{loss}	Amount of C lost from specified pool in a given time-step	$C_{\mathrm{pool,t-1}}\left(1 - \exp\left(-k_{\mathrm{pool}} \times r_{\mathrm{mod}}\right)\right)$	t ha^{-1}	(1)
k_{pool}	Rate constant for decomposition of specified C pool	k_{DPM} = 08333; k_{RPM} = 0.025; k_{BIO} = 0.055; k_{HUM} = 0.0017.	month^{-1}	(1)
r_{mod}	Overall rate modifier	$r_{\mathrm{temp}} \times r_{\mathrm{wat}} \times r_{\mathrm{pH}} \times r_{\mathrm{sal}}$		(1)
<u>Temperature rate modifier</u>				
r_{temp}	Temperature rate modifier	$\dfrac{47.91}{\left(1 \mp \exp\left({}^{106.06}/_{(T_{\mathrm{a}} + 18.27)}\right)\right)}$		(1)
T_{a}	Air temperature	Recorded weather data	ºC	
<u>Moisture rate modifier</u>				
r_{wat}	Soil moisture rate modifier	$\min\left(1, r_{\mathrm{wat,0}} - \left(1 - r_{\mathrm{wat,0}}\right)\left(\dfrac{V_{\mathrm{wat}} - V_{\mathrm{PWP}}}{V_{\mathrm{FC}} - V_{\mathrm{PWP}} - D_{-100\mathrm{kPa}}}\right)\right)$		(1)
V_{FC}	Water content at field capacity	Table 2	mm	
V_{wat}	Water content of the soil in the given time-step	Table 2	mm	
V_{PWP}	Water content at permanent wilting point	Table 2	mm	
$D_{-100\mathrm{kPa}}$	Deficit in soil water at -100 kPa	$0.444 \times (V_{\mathrm{FC}} - V_{\mathrm{PWP}})$	mm	(1)
<u>Acidity rate modifier</u>				

Symbol	Variable	Value, source or formula	Units	Reference
r_{pH}	Soil pH rate modifier	$0.56 + \left(\frac{\tan^{-1}\left(3.14 \times 0.45 \times (S_{\text{pH}} - 5)\right)}{3.14}\right)$		(4)
S_{pH}	Soil pH	Measured in 0.01M CaCl_2 from field measurements or soil database		
Salinity rate modifier				
r_{sal}	Salinity rate modifier	$\exp(-0.09 \times S_{\text{sal}})$		(5)
S_{sal}	Soil salinity	Measured as electrical conductivity in a 1:5 soil/water suspension from field measurements or soil database		
Carbon inputs, C_{in}				
C_{in}	Carbon inputs to pool1	$\sum_{\text{pool2}}(p_{\text{pool1}} C_{\text{loss,pool2}}) + C_{\text{PI,pool1}} + C_{\text{OW,pool1}}$		(1)
Fate of soil organic carbon after decomposition, p_{pool1}				
p_{HUM}	Proportion of humus produced	$\frac{(1/x)}{(1 + 0.85)}$ $x = 1 + 1.67 \times \left(1.85 + 1.6 \times \exp(-0.0786 \times P_{\text{clay}})\right)$		(1)
p_{BIO}	Proportion of biomass produced	$(1/x) - p_{\text{HUM}}$		(1)
p_{CO2}		$p_{\text{CO2}} = 1 - p_{\text{BIO}} - p_{\text{HUM}}$		(1)
Inputs of carbon to the soil from plant inputs, $C_{\text{PI,pool1}}$				
$C_{\text{PI,DPM}}$	Plant inputs of C to DPM	$C_{\text{PI,mon}} \times \frac{p_{\text{D:R,PI}}}{(1 + p_{\text{D:R,PI}})}$	t ha^{-1}	(1)
$p_{\text{D:R,PI}}$	Proportion of DPM to RPM in plant input	Arable = 1.44; grassland = 0.67; forest and scrub = 0.25		(1)
$C_{\text{PI,mon}}$	Plant input of C in given month	$C_{\text{PI}}\left(\frac{\exp\left(-k_{\text{PI,C}} \times (t_{\text{harv}} - t_{\text{mon}})\right)}{\sum_{\text{i}} \exp\left(-k_{\text{PI,C}}(t_{\text{harv}} - t_{\text{mon}})\right) / p_{\text{IH,i}}}\right)$ i = sowing to harvest month		Modified from (3)
$p_{\text{IH,i}}$	Proportional harvest index of crop i	$I_{\text{H,i}} / I_{\text{H,max}}$		
$I_{\text{H,i}}$	Harvest index of crop i	Literature values		
$I_{\text{H,max}}$	Maximum harvest index of crops in the rotation	Literature values		
C_{PI}	Plant input over the whole growing season	$C_{\text{PI}} \times p_{\text{PI:NPP}} \times C_{\text{npp,atyp}} / C_{\text{npp,typ}}$	t ha^{-1}	(2)
$p_{\text{PI:NPP}}$	Proportion of net primary production incorporated in the soil	Literature values		
$C_{\text{npp,atyp}}$	Carbon net primary production in an atypical year	Table 3	t ha^{-1}	
$C_{\text{npp,typ}}$	Carbon net primary production in a typical year	Table 3	t ha^{-1}	

Symbol	Variable	Value, source or formula	Units	Reference
$k_{\mathrm{PI,C}}$	Constant describing the shape of the exponential curve for C input	Arable = 0.6; grassland, forest and scrub = 0.	month^{-1}	(3)
t_{harv}	Harvest month	Input data	month	
t_{mon}	Current month	Time-step counter	month	
Inputs of carbon to the soil from organic wastes, $C_{\mathrm{OW,pool1}}$				
$C_{\mathrm{OW,DPM}}$	Amount of organic waste passed to the DPM pool this month	$C_{\mathrm{OW}} \times \dfrac{p_{\mathrm{D:H,OW}}(1 - p_{\mathrm{IOM,OW}})}{(1 + p_{\mathrm{D:H,OW}})}$	t ha^{-1}	(6)
C_{OW}	Amount of C added in organic waste inputs this month	$p_{\mathrm{D:H,OW}} \times M_{\mathrm{OW}}$	t ha^{-1}	
$p_{\mathrm{C,OW}}$	Proportion of C in organic waste	Local measurements or literature values		
M_{OW}	Amount of organic waste input this month	Input data or animal production model (Table 5)	t ha^{-1}	
$p_{\mathrm{D:H,OW}}$	Ratio of DPM:HUM in the active organic waste added	Fresh waste = 31.45, compost = 0.07; bioslurry = 0.14; biochar = 0.05		(6)
$p_{\mathrm{IOM,OW}}$	Proportion of IOM in organic waste	Biochar = 0.5; fresh waste, compost and bioslurry = 0.		(6)
$C_{\mathrm{OW,HUM}}$	Amount of organic waste passed to the HUM pool this month	$C_{\mathrm{OW}} \times \dfrac{(1 - p_{\mathrm{IOM,OW}})}{(1 + p_{\mathrm{D:H,OW}})}$		(6)
Inert organic matter				
C_{IOM}	C in IOM pool	$C_{\mathrm{IOM,start}} + C_{\mathrm{OW,IOM}}$		
$C_{\mathrm{IOM,start}}$	C in IOM pool at start of the simulation	$0.049 \times ({C_{\mathrm{meas}}}^{1.139})$	t ha^{-1}	(7)
C_{meas}	Measured C content of the soil	Local measurements or soil database	t ha^{-1}	
$C_{\mathrm{OW,IOM}}$	Amount of organic waste passed to the IOM pool this month	$p_{\mathrm{IOM,OW}} \times C_{\mathrm{OW}}$	t ha^{-1}	(6)
$p_{\mathrm{IOM,OW}}$	Proportion of IOM in organic waste	Biochar = 0.5; Farmyard manure, compost and bioslurry = 0.		(6)

Note: (1) Coleman and Jenkinson (1996); (2) Smith et al. (2005); (3) Bradbury et al. (1993); (4) Parton et al. (1996); (5) Setia et al. (2012); (6) Smith et al. (2014); (7) Falloon et al. (1998)

2.2.2. Soil water

Soil water is simulated using a simple piston flow approach, as described by Bradbury et al. (1993) (Table 2). For simplicity in ORATOR and because the monthly time-step is longer than would usually be required for water to move through the profile, a single layer is used to simulate water movement to the depth of available measurements of soil properties, rather than dividing the profile up into layers as is done in some models with shorter time steps (e.g. Bradbury et al., 1993). The soil water content is initialised to the average value between field capacity and permanent wilting point. The water balance is tracked each month during the steady state run; once steady state is achieved, this gives an estimate of soil water content at the start of the dynamic simulation. The soil water in any month is given by the balance of soil water at the start of the month, and any inputs from rainfall and irrigation less any losses by runoff, drainage and evapotranspiration. The soil is allowed to fill up to the water content at field capacity before it runs off or drains; no description is currently included of saturation of the soil. The water available to the plant is calculated as the difference between the volumetric water contents at any given time and the water held in the soil at permanent wilting point, and is allowed to drain, evaporate or be transpired by the plant down to the permanent wilting point. Potential evapotranspiration is calculated as described by Thornthwaite (1948), proportioned according to the depth of simulations and the maximum rooting depth of the plant. Field capacity and permanent wilting point are determined using either standard equations (Tóth et al., 2015), or can be estimated using locally derived pedotransfer functions from laboratory analysis of intact cores; these are recalculated at each time-step of the simulation to account for the impact of changes in SOC on soil water.

Table 2

Simulation of soil water. Note: Input data are shown in shaded cells.

Symbol	**Variable**	**Value, source or formula**	**Units**	**Reference**
Available water in the given depth of soil, $V_{\mathrm{wat,t}}$				
$V_{\mathrm{wat,t}}$	Water content of the soil at time *t*	$\max\left(\min\left(\left(V_{\mathrm{wat,t-1}} + V_{\mathrm{rain}} + V_{\mathrm{irrig}} - V_{\mathrm{PET}}\right), V_{\mathrm{FC}}\right) V_{\mathrm{PWP}}\right)$	mm	(1)
$V_{\mathrm{wat,t-1}}$	Water content of the soil in the previous time-step to time *t*	Water content at the start of the simulation from initialisation plus the balance of any inputs and losses in earlier months of the simulation	mm	
V_{rain}	Rainfall	Recorded weather data	mm	
V_{irrig}	Irrigation	Recorded input data	mm	
Potential evapotranspiration, V_{PET}				
V_{PET}	Potential evapotranspiration	$16\left(\frac{n_{\mathrm{days,mon}}}{30}\right)\left(\frac{L}{12}\right)\left(\frac{10 \times T_{a,mon}}{I_{\mathrm{heat}}}\right)^{\varepsilon}$	mm month^{-1}	(2)

Symbol	Variable	Value, source or formula	Units	Reference
$n_{\mathrm{days,mon}}$	Number of days in the month			
L	Day length	$= \left(\frac{24}{\pi}\right) \cos^{-1}\left(-\tan(\phi)\tan(\delta)\right)$	hrs	(3)
ϕ	Latitude	Local measurements	rad	
δ	Declination of the sun	$0.006918 - 0.399912\cos(\theta_{\mathrm{d}})$ $+ 0.070257\sin(\theta_{\mathrm{d}})$ $- 0.006758\cos(2\theta_{\mathrm{d}})$ $+ 0.000907\sin(2\theta_{\mathrm{d}})$ $- 0.002697\cos(3\theta_{\mathrm{d}})$ $+ 0.001480\sin(3\theta_{\mathrm{d}})$		
θ_{d}	Date in Julian days expressed as an angle	$2\pi\left(\frac{n_{\mathrm{todate}}}{365}\right)$	rad	
n_{todate}	Number of Julian days since 01/01	Date		
$T_{a,mon}$	Average monthly temperature	Local measurements or weather database	°C	
ε	Dimensionless exponent function	$6.75 \text{ x } 10^{-7} I_{\mathrm{heat}}{}^{3} - 7.71 \text{ x } 10^{-3} I_{\mathrm{heat}}{}^{2}$ $+ 1.792 \text{ x } 10^{-2} I_{\mathrm{heat}}$ $+ 4.0239 \text{ x } 10^{-1}$		(2)
I_{heat}	Heat index	$\sum_{\mathrm{mon}=1}^{12}\left(\frac{T_{\mathrm{a,mon}}}{5}\right)^{1.514}$		(2)
$V_{\mathrm{PET,d}}$	Potential evapotranspiration from the selected soil depth	$\min\left(V_{\mathrm{PET}}, V_{\mathrm{PET}}\left(\frac{d}{d_{\mathrm{max}}}\right)\right)$		
d	Simulation depth	Soil measurements	cm	
d_{max}	Maximum rooting depth	Field observations for crops	cm	
Water content at field capacity, V_{FC}				
V_{FC}	Water content at field capacity	$\frac{\theta_{\mathrm{FC}} \times d}{10}$	mm	
θ_{FC}	Volumetric water content at field capacity	$24.49 - 18.87\left(\frac{1}{1+P_{\mathrm{C}}}\right) + 0.4527(P_{\mathrm{clay}})$ $+ 0.1535(P_{\mathrm{silt}})$ $+ 0.1442(P_{\mathrm{silt}})\left(\frac{1}{1+P_{\mathrm{C}}}\right)$ $- 0.00511(P_{\mathrm{silt}})(P_{\mathrm{clay}})$ $+ 0.08676(P_{\mathrm{clay}})\left(\frac{1}{1+P_{\mathrm{C}}}\right)$	%	(4)
P_{C}	Carbon content	Local measurements or soil database	%	
P_{clay}	Clay content	Local measurements or soil database	%	
P_{silt}	Silt content	Local measurements or soil database	%	
d	Simulated soil depth	Local measurements of soil database	cm	
Water content at permanent wilting point, V_{PWP}				
V_{PWP}	Water content at permanent wilting point	$\frac{\theta_{\mathrm{PWP}} \times d}{10}$	mm	
θ_{PWP}	Volumetric water content at permanent wilting point	$9.878 + 0.2127(P_{\mathrm{clay}}) - 0.08366(P_{\mathrm{silt}})$ $- 7.67\left(\frac{1}{1+P_{\mathrm{C}}}\right)$ $+ 0.003853(P_{\mathrm{silt}})(P_{\mathrm{clay}})$ $+ 0.233(P_{\mathrm{clay}})\left(\frac{1}{1+P_{\mathrm{C}}}\right)$ $+ 0.09498(P_{\mathrm{silt}})\left(\frac{1}{1+P_{\mathrm{C}}}\right)$	%	(4)

Note: (1) Bradbury et al. (1993); (2) Thornthwaite (1948); (3) Kirk (2011); (4) Tóth et al. (2015)

2.2.3. Soil nutrients

Only soil N is included in this study and is described in detail below. The simulation of other nutrients (phosphorus and potassium) was excluded for brevity and will be published elsewhere. Following the approach outlined by Smith et al. (2010), N is assumed to be held in 6 pools in the soil; mineral N (nitrate and ammonium) and organic N (DPM, RPM, BIO and HUM-N). The soil organic matter pools (BIO and HUM-N) are assumed to have a constant C:N ratio (8.5 after Bradbury et al., 1993). The C:N ratio of the undecomposed plant matter pools (DPM and RPM) is dependent on the C:N ratios of the plant debris, crop residues or organic manure added to the soil. The amount of ammonium is recalculated each month according to inputs from the atmosphere, fertilisers and mineralisation, and losses by immobilisation, nitrification, volatilisation and crop uptake. The amount of nitrate in the soil is recalculated according to inputs from the atmosphere, fertilisers and nitrification, and losses by immobilisation, leaching, denitrification and crop uptake. Because the time step of the model is long (1 month), if the loss processes were calculated sequentially, as is often done in models with a shorter time step (e.g. Bradbury et al., 1993; Smith et al., 2010), most N would be available for the loss process that was applied first. This would result in an unrealistically high rate of loss for the processes applied first, and an erroneously low rate of loss for the process applied last. Therefore, the potential loss by each process is initially calculated assuming no other loss processes occur, and then the loss from each is adjusted using a “loss adjustment ratio” to account for the demands from other processes. The loss adjustment ratio is given by the proportion of the potential loss by this process to the potential loss from all processes. In this way, all processes are assumed to occur simultaneously and are proportioned according to the size of their demand (Table 3).

The inputs of ammonium from the atmosphere are estimated from a constant annual N deposition determined according to location, assuming that 50% of the deposited N is in the form of ammonium. Inputs from fertilisers are dependent on the amount and type of fertiliser applied. Mineralisation and immobilisation are calculated from the release or uptake of N by decomposing organic matter (Bradbury et al., 1993). Using the equations given in Table 3, release or uptake of N on organic matter decomposition is calculated from the amount needed to maintain a stable C:N ratio in the soil organic matter pools. The released N is assumed to be mineralised to ammonium. The uptake of N is assumed to be immobilised from the ammonium pool first with any additional N requirement being immobilised from the nitrate pool; if there is remaining requirement for N uptake after all mineral N has been taken up, the rate of decomposition is reduced to account for this limitation as described in Table 1. Nitrification of ammonium is calculated using a first order equation that is dependent on the ammonium content of the soil, modified according to temperature, moisture, pH and salinity in the same way as for aerobic decomposition (Table 3). Volatilisation is calculated as a proportion of the ammonium N applied in fertiliser or manure in that month when rainfall is less than a given level (Bradbury et al., 1993). Ammonium is taken up by the crop according to crop N demand and the proportion of the soil mineral N that is in the form of ammonium.

Inputs of nitrate from the atmosphere and fertilisers are estimated in the same way as the inputs of ammonium, and inputs by nitrification are assumed to be equivalent to the losses of ammonium to nitrification. The amount of nitrate immobilised is given by the remaining N needed to maintain a stable C:N ratio in the soil organic matter after ammonium has been immobilised. Leaching losses are calculated according to the concentration of nitrate in the soil solution and the drainage of water as given in Table 2. After Bell et al. (2012), denitrification losses are estimated from a maximum potential rate of denitrification, adjusted according to the amount of nitrate in the soil, the water content of the soil and the biological activity; CO_2 produced by soil organic matter decomposition that month is used as a surrogate for biological activity. The denitrified N is then partitioned into di-nitrogen gas and nitrous oxide according to the moisture and nitrate content of the soil. Similarly to ammonium crop uptake, nitrate is taken up by the crop according to crop N demand and the proportion of the soil mineral N that is in the form of nitrate.

Table 3

Simulation of soil nitrogen. Note, N = nitrogen; C = carbon; DPM = decomposable plant material; RPM = resistant plant material; BIO = rapidly decomposing organic matter, “biomass”; HUM = slowly decomposing organic matter, “humus”; IOM = inert organic matter. Input data are shown in shaded cells.

Symbol	Variable	Value, source or formula	Units	Reference
Amount of nitrate-N in the soil, N_{NO3}				
N_{NO3}	Amount of nitrate-N in the soil	$N_{\mathrm{NO3,start}} + N_{\mathrm{NO3,in}} - \left(f_{\mathrm{NO3,loss}} \times N_{\mathrm{NO3,loss}}\right)$	kg ha^{-1}	(1)
$N_{\mathrm{NO3,start}}$	Amount of nitrate-N at the start of the time-step	Initialised to $N_{\mathrm{NO3,min}}$ and then the balance of any changes occurring in previous time-steps	kg ha^{-1}	(1)
$N_{\mathrm{NO3,min}}$	Minimum possible amount of nitrate-N	Minimum level of nitrate N, as observed in the field for that experiment, or set to 0 kg ha^{-1}	kg ha^{-1}	(1)
$f_{\mathrm{NO3,loss}}$	Nitrate loss adjustment factor	$\frac{\left(N_{\mathrm{NO3,start}} + N_{\mathrm{NO3,in}}\right)}{N_{\mathrm{NO3,loss}}}$ if ($N_{\mathrm{NO3,loss}} \leq \left(N_{\mathrm{NO3,start}} + N_{\mathrm{NO3,in}}\right)$), $f_{\mathrm{NO3,loss}} = 1$		
Inputs of nitrate-N, $N_{\mathrm{NO3,in}}$				
$N_{\mathrm{NO3,in}}$	Input of nitrate-N	$N_{\mathrm{NO3,atm}} + N_{\mathrm{NO3,fert}} + N_{\mathrm{NO3,nitrif}}$	kg ha^{-1}	(1)
Atmospheric inputs				
$N_{\mathrm{NO3,atm}}$	Atmospheric deposition of nitrate-N	$p_{\mathrm{NO3,atm}} \times N_{\mathrm{atm}}$	kg ha^{-1}	(1)
$p_{\mathrm{NO3,atm}}$	Prop. nitrate-N in atmospheric deposition	Assumed 0.5		
N_{atm}	Total atmospheric N deposition in the time-step	Input data	kg ha^{-1}	
Fertiliser inputs				
$N_{\mathrm{NO3,fert}}$	Fertiliser inputs to the nitrate-N pool	Input data	kg ha^{-1}	
Nitrification inputs				
$N_{\mathrm{NO3,nitrif}}$	Input of nitrified-N to the nitrate pool	Assumed equivalent to nitrification of ammonium-N	kg ha^{-1}	
Losses of nitrate-N, $N_{\mathrm{NO3,loss}}$				
$N_{\mathrm{NO3,loss}}$	Loss of nitrate-N	$N_{\mathrm{NO3,immob}} + N_{\mathrm{NO3,leach,t}} + N_{\mathrm{denit}} + N_{\mathrm{NO3,crop}}$	kg ha^{-1}	(1)
Immobilisation losses				
$N_{\mathrm{NO3,immob}}$	Immobilisation of nitrate-N	$\min\left(-\min\left(\left(N_{\mathrm{soil}} - N_{\mathrm{NH4,immob}}\right), 0\right), N_{\mathrm{NO3,min}}\right)$	kg ha^{-1}	(1)

Symbol	Variable	Value, source or formula	Units	Reference
N_{soil}	Soil N supply	See below	kg ha^{-1}	
$N_{\mathrm{NH4,immo}}$	Immobilisation of ammonium-N	See below	kg ha^{-1}	
Leaching losses				
$N_{\mathrm{NO3,leach}}$	Leaching of nitrate-N	$\frac{(N_{\mathrm{NO3,start}} + N_{\mathrm{NO3,in}} - N_{\mathrm{NO3,min}})}{(V_{\mathrm{wat,t-1}} + V_{\mathrm{rain}} - V_{\mathrm{PET,d}})} \times V_{\mathrm{wat,drained}}$	kg ha^{-1}	(1)
$V_{\mathrm{wat,t-1}}$	Water content of the soil in the previous time-step to time *t*	Table 2	mm	
V_{rain}	Rainfall	Table 2	mm	
$V_{\mathrm{PET,d}}$	Potential evapotranspiration from the selected soil depth	Table 2	mm	
$V_{\mathrm{wat,draine}}$	Water drained from the soil	$\max\left(\left((V_{\mathrm{rain}} - V_{\mathrm{PET,d}}) - (V_{\mathrm{FC}} - V_{\mathrm{wat,t-1}})\right), 0\right)$	mm	(1)
Denitrification losses				
N_{denit}	Losses of nitrate-N by denitrification	$N_{\mathrm{denit,max}} \times m'_{\mathrm{NO3}} \times m'_{\mathrm{wat}} \times m'_{\mathrm{bio}}$	kg ha^{-1}	(2)
$N_{\mathrm{denit,max}}$	Maximum potential rate of denitrification in a month	$\min(N_{\mathrm{NO3}}, 0.2 \times d \times n_{\mathrm{days,mon}})$	kg ha^{-1}	(3)
$n_{\mathrm{days,mon}}$	Number of days in the month			
m'_{NO3}	Nitrate rate modifier	$\frac{N_{\mathrm{NO3}}}{(N_{\mathrm{d50}} + N_{\mathrm{NO3}})}$		
N_{d50}	Nitrate-N at which denitrification is 50% of full potential	$3.3 \times d$	kg ha^{-1}	(3)
d	Simulation depth	Soil measurements	cm	
m'_{wat}	Soil moisture rate modifier	$\min\left(1, \left(\frac{\max\left(0, {}^{(V_{\mathrm{wat}} - V_{\mathrm{PWP}})}/_{(V_{\mathrm{FC}} - V_{\mathrm{PWP}})}\right) - 0.62}{0.38}\right)^{1.74}\right)$		(4)
V_{wat}	Water content of the soil in time-step *t*	Table 2	mm	
V_{FC}	Water content at field capacity	Table 2	mm	
V_{PWP}	Water content at permanent wilting point	Table 2	mm	
m'_{bio}	Biological activity rate modifier	$\min(1, C_{\mathrm{CO2}} \times 0.1)$		(1)
C_{CO2}	CO_2-C produced by aerobic decomposition	Table 1		
$N_{\mathrm{denit,N2O}}$	Nitrous oxide–N produced on denitrification	$(1 - (p_{\mathrm{w}} \times p_{\mathrm{NO3}})) \times N_{\mathrm{denit}}$	kg ha^{-1}	(2)
p_{w}	Prop.N_2 produced according to soil water	$0.5 \times {}^{(V_{\mathrm{wat}} - V_{\mathrm{PWP}})}/_{(V_{\mathrm{FC}} - V_{\mathrm{PWP}})}$		(2)
p_{NO3}	Prop.N_2 produced according to nitrate	$1 - \left(\frac{N_{\mathrm{NO3}}}{(40d) + N_{\mathrm{NO3}}}\right)$		(2)
Crop uptake				
$N_{\mathrm{NO3,crop}}$	Crop N demand from the nitrate pool	$N_{\mathrm{crop}} \times \left({}^{N_{\mathrm{NO3}}}/_{(N_{\mathrm{NO3}} + N_{\mathrm{NH4}})}\right)$	kg ha^{-1}	

Symbol	Variable	Value, source or formula	Units	Reference
N_{crop}	Crop N demand this month	$p_{\mathrm{N:opt}} \times N_{\mathrm{opt}} \Big/ t_{\mathrm{grow}}$	kg ha^{-1}	
$p_{\mathrm{N:opt}}$	Proportion of the optimum supply of N in the soil	Table 4		
N_{opt}	N supply required for the optimum yield	Table 4	kg ha^{-1}	
t_{grow}	Months in the growing season	Input data		
Amount of ammonium-N in the soil, N_{NH4}				
N_{NH4}	Amount of ammonium-N in the soil	$N_{\mathrm{NH4,start}} + N_{\mathrm{NH4,in}} - \left(f_{\mathrm{NH4,loss}} \times N_{\mathrm{NH4,loss}}\right)$	kg ha^{-1}	(1)
$N_{\mathrm{NH4,start}}$	Amount of ammonium-N at the start of the time-step	Initialised to $N_{\mathrm{NH4,min}}$ and then the balance of any changes occurring in previous time-steps	kg ha^{-1}	(1)
$N_{\mathrm{NH4,min}}$	Minimum possible amount of ammonium-N	Minimum level of ammonium N, as observed in the field for that experiment, or set to 0 kg ha^{-1}	kg ha^{-1}	(1)
$f_{\mathrm{NH4,loss}}$	Ammonium loss adjustment factor	$\dfrac{\left(N_{\mathrm{NH4,start}} + N_{\mathrm{NH4,in}}\right)}{N_{\mathrm{NH4,loss}}}$ if ($N_{\mathrm{NH4,loss}} \leq \left(N_{\mathrm{NH4,start}} + N_{\mathrm{NH4,in}}\right)$), $f_{\mathrm{NH4,loss}} = 1$		
Inputs of ammonium-N, $N_{\mathrm{NH4,in}}$				
$N_{\mathrm{NH4,in}}$	Input of ammonium-N	$N_{\mathrm{NH4,atm}} + N_{\mathrm{NH4,fert}} + N_{\mathrm{NH4,OW}} + N_{\mathrm{NH4,miner}}$	kg ha^{-1}	(1)
Atmospheric inputs				
$N_{\mathrm{NH4,atm}}$	Atmospheric deposition of ammonium-N	$N_{\mathrm{NH4,atm}} = p_{\mathrm{NH4,atm}} \times N_{\mathrm{atm}}$	kg ha^{-1}	
$p_{\mathrm{NH4,atm}}$	Prop.ammonium in the atmospheric deposition	Assumed 0.5		
Fertiliser inputs				
$N_{\mathrm{NH4,fert}}$	Fertiliser inputs to the ammonium-N pool	Input data	kg ha^{-1}	
Organic waste inputs				
$N_{\mathrm{NH4,OW}}$	Organic waste inputs to the ammonium-N pool	$\left(1000 \times p_{\mathrm{NH4:N,OW}} \times p_{\mathrm{C,OW}} \times M_{\mathrm{OW}}\right) \Big/ p_{\mathrm{C:N,OW}}$	kg ha^{-1}	
$p_{\mathrm{NH4:N,OW}}$	Proportion of N in organic waste that is ammonium or urea	Local experiments or literature values		
$p_{\mathrm{C,OW}}$	Proportion of C in organic waste	Local experiments or literature values		
$p_{\mathrm{C:N,OW}}$	Average C:N ratio of organic waste	Local experiments or literature values		
M_{OW}	Amount of organic waste input this month	Input data or animal production model (Table 5)	t ha^{-1}	
Soil supply				
$N_{\mathrm{NH4,miner}}$	Input of mineralised-N to the ammonium pool	$\max(N_{\mathrm{soil}}, 0)$	kg ha^{-1}	
Losses of ammonium-N, $N_{\mathrm{NH4,loss}}$				
$N_{\mathrm{NH4,loss}}$	Loss of ammonium-N	$N_{\mathrm{NH4,immob}} + N_{\mathrm{NH4,nitrif}} + N_{\mathrm{NH4,volat}} + N_{\mathrm{NH4,crop}}$	kg ha^{-1}	(1)

Symbol	Variable	Value, source or formula	Units	Reference
Immobilisation losses				
$N_{\text{NH4,immob}}$	Immobilisation of ammonium-N	$\min\left(-\min(N_{\text{soil}}, 0)\,, N_{\text{NH4,min}}\right)$	kg ha^{-1}	(1)
N_{soil}	Soil N supply	$N_{\text{release}} - N_{\text{adjust}}$	kg ha^{-1}	(1)
N_{release}	Release of nutrient associated with CO$_2$-C loss	$p_{\text{CO2}}\left(\left(\frac{1000}{p_{\text{C:N,DPM}}}\right)C_{\text{loss,DPM}} + \left(\frac{1000}{p_{\text{C:N,RPM}}}\right)C_{\text{loss,RPM}} + \left(\frac{1000}{p_{\text{C:N,soil}}}\right)C_{\text{loss,BIO}} + \left(\frac{1000}{p_{\text{C:N,HUM}}}\right)C_{\text{loss,HUM}}\right)$	kg ha^{-1}	(1)
p_{CO2}	Proportion of CO$_2$ produced on decomposition	Table 1		
$C_{\text{loss,pool}}$	C loss from pool	Table 1	t ha^{-1}	
$p_{\text{C:X,DPM}}$	C:X ratio of pool (X = nutrient = N)	$\frac{\left(C_{\text{DPM,last}} + C_{\text{PI,DPM}} + C_{\text{OW,DPM}}\right)}{\left(\left({C_{\text{DPM,last}}}/{p_{\text{C:X,DPM,last}}}\right) + \left({C_{\text{PI,DPM}}}/{p_{\text{C:X,plant}}}\right) + \left({C_{\text{OW,DPM}}}/{p_{\text{C:X,OW}}}\right)\right)}$		
$C_{\text{DPM,last}}$	Stock of C in the DPM pool in the last time step	Table 1	t ha^{-1}	
$C_{\text{PI,DPM}}$	Inputs of C to the DPM pool from plant inputs	Table 1	t ha^{-1}	
$C_{\text{OW,DPM}}$	Inputs of C to the DPM pool from organic wastes	Table 1	t ha^{-1}	
$p_{\text{C:X,DPM,last}}$	C:nutrient ratio of the DPM pool in the last time-step	Previous time-step		
$p_{\text{C:X,plant}}$	C:nutrient ratio of plant inputs (X = nutrient = N)	**¡Error! No se encuentra el origen de la referencia.** Parameter measured for specific crop type		
$p_{\text{C:X,OW}}$	C:nutrient ratio of organic waste inputs (X = nutrient = N)	Parameter measured for specific organic waste type		

Symbol	Variable	Value, source or formula	Units	Reference
N_{adjust}	Adjustment of N content	$p_{\mathrm{BIO}}\left(\left(\left(\left(\frac{1000}{p_{\mathrm{C:N,soil}}}\right)-\left(\frac{1000}{p_{\mathrm{C:N,DPM}}}\right)\right)C_{\mathrm{loss,DPM}}+\left(\left(\frac{1000}{p_{\mathrm{C:N,soil}}}\right)-\left(\frac{1000}{p_{\mathrm{C:N,RPM}}}\right)\right)C_{\mathrm{loss,RPM}}\right)+p_{\mathrm{HUM}}\left(\left(\left(\frac{1000}{p_{\mathrm{C:N,HUM}}}\right)-\left(\frac{1000}{p_{\mathrm{C:N,DPM}}}\right)\right)C_{\mathrm{loss,DPM}}+\left(\left(\frac{1000}{p_{\mathrm{C:N,HUM}}}\right)-\left(\frac{1000}{p_{\mathrm{C:N,RPM}}}\right)\right)C_{\mathrm{loss,RPM}}\right)$	kg ha^{1}	(1)
$p_{\mathrm{C:N,soil}}$	C:N ratio of stable soil	8.5		(1)
Nitrification losses				
$N_{\mathrm{NH4,nitrif}}$	Nitrified ammonium-N	$\min\left(N_{\mathrm{NH4}}\left(1-\exp(-k_{\mathrm{nitrif}}r_{\mathrm{mod}}r_{\mathrm{inhibit}})\right),N_{\mathrm{min,NH4}}\right)$	kg ha^{-1}	(1)
k_{nitrif}	Rate constant for nitrification	2.6	month^{-1}	(1)
r_{mod}	Rate modifying factor	Table 1		
r_{inhibit}	Inhibition rate modifier	Accounts for application of nitrification inhibitors		
$N_{\mathrm{nitrif,N2O}}$	Nitrified N lost as N_2O	$N_{\mathrm{NH4,nitrif}}\times\left(\left(p_{\mathrm{N2O,FC}}\times\frac{V_{\mathrm{wat}}}{V_{\mathrm{FC}}}\right)+\left(p_{\mathrm{nitrif,gas}}\times(1-p_{\mathrm{NO}})\right)\right)$	kg ha^{-1}	(2)
$p_{\mathrm{N2O,FC}}$	Proportion of N_2O produced due to partial nitrification at field capacity	0.02		(2)
$p_{\mathrm{nitrif,gas}}$	Proportion of full nitrification lost as gas	0.02		(2)
p_{NO}	Proportion of full nitrification gaseous loss that is NO	0.4		(2)
$N_{\mathrm{nitrif,NO}}$	Nitrified N lost as NO	$N_{\mathrm{NH4,nitrif}}\times\left(\left(p_{\mathrm{N2O,FC}}\times\frac{V_{\mathrm{wat}}}{V_{\mathrm{FC}}}\right)+\left(p_{\mathrm{nitrif,gas}}\times p_{\mathrm{NO}}\right)\right)$	kg ha^{-1}	(2)
Volatilisation losses				
$N_{\mathrm{NH4,volat}}$		if $(V_{\mathrm{rain}}<V_{\mathrm{rain,crit}})$, $p_{\mathrm{volat}}\times\left(N_{\mathrm{NH4,manure}}+N_{\mathrm{NH4,fert}}\right)$	kg ha^{-1}	(1)
$V_{\mathrm{rain,crit}}$	Volatilisation occurs below this rainfall	21	mm	(1)
p_{volat}	Proportion of applied	0.15		(1)

Symbol	Variable	Value, source or formula	Units	Reference
	ammonium or urea-N volatilised			
$N_{\mathrm{NH4,manur}}$	Amount of ammonium or urea-N in manure	Input data	kg ha^{-1}	
$N_{\mathrm{NH4,fert}}$	Amount of ammonium or urea-N in fertiliser	Input data	kg ha^{-1}	
Crop uptake				
$N_{\mathrm{NH4,crop}}$	Crop uptake of ammonium-N	$N_{\mathrm{crop}} \times \left({N_{\mathrm{NH4}}}/{(N_{\mathrm{NO3}} + N_{\mathrm{NH4}})} \right)$	kg ha^{-1}	(1)

Note: (1) Bradbury et al. (1993); (2) Bell et al. (2012); (3) Henault and Germon (2000); (4) Grundmann and Rolston (1987)

2.3. Crop production

Accurate simulation of crop yield is notoriously difficult and requires a considerable amount of data due to the wide range of factors that can inhibit crop growth, such as diseases, pests, nutrients and water. Therefore, ORATOR instead simulates *change* in crop production using a ratio approach driven by only the variables that are expected to change as a result of the environmental and management factors that are the focus of this model. These are growing degree days, water stress and nutrient availability, which are affected by both climatic conditions and the soil properties influenced by organic matter inputs (Table 4). This approach aims to increase the accuracy possible when only limited input data are available to predict yield by scaling the results using input values of “typical yield” for the specific farm or area being simulated. The typical yield is multiplied by the ratio of plant production estimated for the simulation year (the “atypical” year) to plant production estimated for the steady state conditions (the “typical” year). It is assumed that the factors not explicitly described in the model have similar impacts on yield in both typical and atypical conditions. This assumption will break down if unusual or catastrophic conditions for crop growth occur in the year of simulation, such as a disease outbreak or atypical pest attack.

The change in net primary production according to weather conditions, expressed as growing degree days and the water stress (given by the ratio of actual to potential evapotranspiration), is calculated by the equations given in Table 4 (Zaks et al., 2007). The yield according to nutrient limitation (only N presented here) is calculated according to the proportion of the optimum nutrient requirement that is available, and the yield response to available nutrient as described by Reid (2002). The parameters needed to describe optimum nutrient requirement and yield response are easily obtained from standard crop response field trials (Table 4). The adjustments to crop production that would occur due to weather and nutrient limitations are then combined to provide a single adjustment to crop production as outlined in Table 4.

Table 4

Simulation of changes in crop production. Note, N = nitrogen; P = phosphorus; K = potassium; C = carbon. Input data are shown in shaded cells.

Symbol	Variable	Value, source or formula	Units	Reference
Yield in an atypical year, $M_{\mathrm{yld,atyp}}$				
$M_{\mathrm{yld,atyp}}$	Yield in an atypical year	$C_{\mathrm{yld,typ}} \times p_{\mathrm{plant,atyp}}$	t ha^{-1}	
$M_{\mathrm{yld,typ}}$	Yield in a typical year	Input data	t ha^{-1}	
Ratio of plant production in an atypical year compared to a typical year, $p_{\mathrm{plant,atyp}}$				
$p_{\mathrm{plant,atyp}}$	Ratio of plant production in an atypical year compared to a typical year	${C_{\mathrm{npp,atyp}}}/{C_{\mathrm{npp,typ}}}$; $\left(p_{\mathrm{plant,atyp}} < {M_{\mathrm{yld,max}}}/{M_{\mathrm{yld,typ}}}\right)$		
$M_{\mathrm{yld,max}}$	Maximum potential crop yield	Derived from nutrient response curves	t ha^{-1}	(1)
Net primary production according to nutrient, growing degrees and water stress, C_{npp}				
C_{npp}	Net primary production of C (typ = typical year; atyp = atypical year; mon = this month)	$\min_{\mathrm{X}}\left[C^{*}_{\mathrm{npp,X}}\right]$	t ha^{-1}	(1)
$C^{*}_{\mathrm{npp,X}}$	Net primary production calculated according to limitation of nutrient X	$p_{\mathrm{yld:opt}} \times C^{**}_{\mathrm{npp}}$; $\left(0 \leq p_{\mathrm{yld:opt}} \leq 1\right)$	t ha^{-1}	(1)
$p_{\mathrm{yld:opt}}$	Prop. of optimum yield achieved	$(1 + c_{\mathrm{X}}) p_{\mathrm{X:opt}}{}^{c_{\mathrm{X}}} - \left(c_{\mathrm{X}}.\, p_{\mathrm{X:opt}}{}^{(1+c_{\mathrm{X}})}\right)$		(1)
c_{X}	Nutrient response coefficient	Calculated by fitting to nutrient response curves for the particular crop		(1)

Symbol	Variable	Value, source or formula	Units	Reference
$p_{\mathrm{X:opt}}$	Prop. of nutrient (N, P or K) available compared to the optimum amount of nutrient	$\frac{(X_{\mathrm{soil}}+X_{\mathrm{fert}}-X_{\mathrm{min}})}{(X_{\mathrm{opt}}-X_{\mathrm{min}})}$; $(0 \le p_{\mathrm{X:opt}} \le 1)$		(1)
X_{soil}	Soil supply of the nutrient	Table 3	kg ha^{-1}	
X_{fert}	Fertiliser input of the nutrient	$p_{\mathrm{eff,fertX}} \times X_{\mathrm{fert,in}}$	kg ha^{-1}	
$p_{\mathrm{eff,fertX}}$		0.33 for broadcast application; 0.61 for band application of N; 1.0 for P and K		(1)
$X_{\mathrm{fert,in}}$	Fertiliser added to the soil	Input data	kg ha^{-1}	
X_{min}	Minimum amount of nutrient that results in a harvestable yield	Calculated by fitting to nutrient response curves for the particular crop	kg ha^{-1}	(1)
X_{opt}	Amount of nutrient required to achieve maximum yield	Calculated by fitting to nutrient response curves for the particular crop	kg ha^{-1}	(1)
Net primary production according to growing degree days and water stress during the growing season, $C^{**}{}_{\mathrm{npp}}$				
$C^{**}{}_{\mathrm{npp}}$	Net primary production of C (typ = typical year; atyp = atypical year; mon = this month)	$27.20 \max\left(0, \left(0.0396 \middle/ \left(1+\exp\left(6.33-1.5\left(\frac{T_{\mathrm{GDD}}}{11500}\right)\right)\right)\right) \times (39.58\, I_{\mathrm{ws}} - 14.52)\right)$	t ha^{-1}	(2)
T_{GDD}	Growing degree days	$\max\left(0, n_{\mathrm{days}} \times (T_{\mathrm{a}} - 5)\right)$	°C day	(2)
n_{days}	Number of days in growing season	Input data		
T_{a}	Average air temperature	Local measurements or weather database	°C	
I_{ws}	Water stress index	$V_{\mathrm{AET}}/V_{\mathrm{PET}}$		(2)
V_{AET}	Actual evapotranspiration from rooting zone	$\min\left(V_{\mathrm{PET}}, 5 \times n_{\mathrm{days,mon}}, (V_{\mathrm{wat}} - V_{\mathrm{PWP}})\right)$	mm	(2)
V_{PET}	Potential evapotranspiration from rooting zone	Table 2	mm	
$n_{\mathrm{days,mon}}$	Number of days in the month			
V_{wat}	Water content of the soil	Table 2	mm	
V_{PWP}	Water content at permanent wilting point	Table 2	mm	

Note: (1) Reid (2002); (2) Zaks et al. (2007)

2.4. Animal production

Animal production in the current simulation year is estimated using a database of typical animal production values for the region giving meat, milk, manure and excreted N (Hererro et al., 2013). The production of each of these outputs is then adjusted in proportion to the available feed in the current simulation year compared to the typical values supplied (Table 5). Depending on the strategy selected, animal production is either (1) maintained by buying or selling the difference in the crop production, or (2) allowed to change in proportion to the change in crop production from the previous harvest. Other strategies may be added according to observed farmer behaviours.

Table 5

Simulation of changes in animal production. Note, N = nitrogen; P = phosphorus; K = potassium; C = carbon. Input data are shown in shaded cells.

Symbol	Variable	Value, source or formula	Units	Reference
Animal production in atypical year, $M_{\text{tot,atyp}}$				
$M_{\text{tot,atyp}}$	Animal production in an atypical year of meat, milk, manure or excreted N	$p_{\text{animal,atyp}} \times M_{\text{tot,typ}}$	kg y^{-1}	
$M_{\text{tot,typ}}$	Animal production in a typical year of meat, milk, manure or excreted N	$n_{\text{animal}} \times M_{\text{prod}}$	kg y^{-1}	
n_{animal}	Number of animals kept on the farm	Input data		
M_{prod}	Animal production per head in typical year of meat, milk, manure or excreted N	From animal production database	kg y^{-1}	(1)
Proportion of animal production achieved in an atypical year compared to a typical year, $p_{\text{animal,atyp}}$				
$p_{\text{animal,atyp}}$	Proportion of animal production in an atypical year compared to a typical year	1 if animal production is maintained by buying in feed; otherwise $\sum_{\text{i}} \left(\frac{p_{\text{plant,atyp,i}} \times P_{\text{feed,i}}}{100} \right) + \frac{P_{\text{feed,buy}}}{100}$		
$p_{\text{plant,atyp,,}}$	Ratio of plant production in an atypical year compared to a typical year for crop i that is used to feed animals	Table 4		
$P_{\text{feed,i}}$	Percentages of calorific feed value supplied to animals from the crop i	Input data		
$P_{\text{feed,buy}}$	Percentage of animal feed bought from	Input data		

Symbol	Variable	Value, source or formula	Units	Reference
	outside sources			

Note: (1) Herrero et al. (2013)

2.5. Water use

The total irrigation needed is estimated by assuming that irrigation compensates for any shortfall in soil water compared to a typical year, limited to the amount of irrigation allowed in a given time-step, which is specified in the input data (Table 6). These simple estimates can be overridden by user inputs if the actual irrigation water collected in a particular year is known.

Table 6

Water use. Note: Input data are shown in shaded cells.

Symbol	Variable	Value, source or formula	Units
Irrigation water required in an atypical year, $V_{\text{irrig,atyp}}$			
$V_{\text{irrig,atyp}}$	Irrigation water required in an atypical year	$V_{\text{wat,typ}} + V_{\text{irrig,typ}} - V_{\text{wat,atyp}}$, where $0 \le V_{\text{irrig,atyp}} \le V_{\text{irrig,max}} / (A \times 10^4)$	mm
$V_{\text{wat,typ}}$	Soil water content in a typical year	Table 2	mm
$V_{\text{irrig,typ}}$	Irrigation water required in an atypical year	Input data	mm
$V_{\text{wat,atyp}}$	Soil water content in an atypical year	Table 2	mm
$V_{\text{irrig,max}}$	Maximum rate of irrigation specified for the site	Input data	$dm^3\ m^{-2}$
A	Area of the piece of land	Input data	ha

2.6. Energy use

The inputs to the model specify the percentages of cooking and lighting fuels obtained from wood, charcoal, crop residues, dung, kerosene and electricity (Table 7). The proportion of fuel available in the current simulation year compared to the typical (steady state) year provides an estimate for the change in organic resources available for use in cooking or lighting. Unless otherwise specified in the inputs, this proportion is assumed to be 1 (no change) for wood, charcoal, kerosene and electricity. For crop residues, the proportion is calculated from the changes in crop production for the crops that are used for fuel. For dung, it is calculated from the change in production across all animals kept on the farm. The energy use in a typical year for cooking and lighting are estimated from either national statistics or the energy use in a typical year specified as an input.

Table 7

Energy use. Note: Input data are shown in shaded cells.

Symbol	**Variable**	**Value, source or formula**	**Units**	**Reference**
Energy available for cooking in an atypical year, $E_{\text{cook,atyp}}$				
$E_{\text{cook,atyp}}$	Energy available for cooking in an atypical year	$E_{\text{cook,typ}} \times \frac{\sum_{\text{fuel}}\left(P_{\text{cook,fuel}} \times p_{\text{fuel,atyp}}\right)}{10^2}$	MJ y^{-1}	
$E_{\text{cook,typ}}$	Energy available for cooking in a typical year	From national statistics or the energy use in a typical year specified as input data	MJ y^{-1}	(1,2)
$P_{\text{cook,fuel}}$	Percentage of cooking fuel obtained from fuel	Input data; fuel = wood, charcoal, crop residues, dung, kerosene and electricity	%	
$p_{\text{fuel,atyp}}$	Proportion of fuel available in atypical compared to typical years			
	…for crop residues	$\sum_{\text{area}}\left(\left(p_{\text{plant,area}}\ P_{\text{area}}\ P_{\text{use,fuel}}\right) \Big/ \sum_{\text{area}}\left(P_{\text{area}}\ P_{\text{use,fuel}}\right)\right)$		
	…for dung	$\sum_{\text{animal}}\left(\left(p_{\text{animal,atyp}} \times n_{\text{animal}}\right) \Big/ \sum_{\text{animal}} n_{\text{animal}}\right)$		
$p_{\text{plant,area}}$	Proportion of plant production in an atypical year compared to a typical year	Table 4		
P_{area}	Percentage of the farm in this area	Input data	%	
$P_{\text{use,fuel}}$	Percentage of the crop type grown in that area that is used for fuel	Input data	%	

$p_{\text{animal,atyp}}$	Proportion of animal production in an atypical year compared to a typical year	Table 5	
n_{animal}	Number of animals of the given type (animal)	Input data	
Note: (1) IEA (2013); (2) UN Statistics Division Energy Statistics Database (2013)			

2.7. Labour

Labour is calculated from entered values specifying the time different members of the household spend collecting water and wood each week, tending livestock and crops each day, and on other essential activities (such as cooking, cleaning the home etc) each day (Table 8). This information needs to be gathered by survey in the village or household under study. Household members are divided into male adults, female adults, male children and female children. This information is then used to estimate the time available for non-agricultural activities, such as leisure, education, petty trading, off-farm work, and how this changes throughout the year.

Table 8

Labour. Note: Input data are shown in shaded cells.

Symbol	Variable	Value, source or formula	Units
Time spent by each person collecting water for household and animal use, t_{water}			
t_{wood}	Average time each person spends collecting woodfuel each day	$\frac{\left(n_{\text{trip,wood}} \times \left(t_{\text{travel,wood}} + t_{\text{gather,wood}}\right)\right)}{7 \times n_{\text{people}}}$	hrs d^{-1}
n_{people}	Number of people in the group	Groups are adult males, adult females, male children, female children	
$n_{\text{trip,wood}}$	Number of trips made by all people in this group (adult male, adult female, male child, female child) each week to collect woodfuel	Input data	
$t_{\text{travel,wood}}$	Average time spent in each trip travelling to and from the place where wood is collected	Input data	hrs

Symbol	Variable	Value, source or formula	Units
$t_{\mathrm{gather,wood}}$	Average time spent in each trip gathering wood	Input data	hrs
Time spent by each person collecting water for household and animal use, t_{water}			
t_{water}	Average time spent by each person collecting water for household and animal use	$t_{\mathrm{water,house}} \times \frac{V_{\mathrm{water,total}}}{V_{\mathrm{water,house}}}$	hrs d^{-1}
$V_{\mathrm{water,total}}$	Total volume of water required each month	$V_{\mathrm{water,house}} + V_{\mathrm{irrig}}$	dm^{3} mnth^{-1}
$V_{\mathrm{water,house}}$	Total amount of water collected for the household and animals each month	$\sum_{\mathrm{i}} \left(\frac{n_{\mathrm{days,month}}}{7} \times n_{\mathrm{trip,water,i}} \times V_{\mathrm{water,trip,i}}\right)$, i = different groups	dm^{3} mnth^{-1}
$n_{\mathrm{days,month}}$	Number of days in the month		
$n_{\mathrm{trip,water,i}}$	Number of trips made by people in this group to collect water	Input data	
$V_{\mathrm{water,trip,i}}$	Volume of water carried in each trip	Input data	dm^{3}
$t_{\mathrm{water,house}}$	Total time spent by each person collecting water for household and animal use	$\frac{\left(n_{\mathrm{trip,water}}\left(t_{\mathrm{travel,water}} + t_{\mathrm{queue,water}}\right)\right)}{\left(7 \times n_{\mathrm{people}}\right)}$	hrs d^{-1}
$n_{\mathrm{trip,water}}$	Number of trips made to collect water	Input data	
$t_{\mathrm{travel,water}}$	Average time spent in each trip travelling to and from the place where water is collected	Input data	hrs
$t_{\mathrm{queue,water}}$	Average time spent queuing for water in each trip	Input data	hrs
Time spent managing livestock, $t_{\mathrm{livestock}}$			
$t_{\mathrm{livestock}}$	Average time spent managing livestock	$\left(t_{\mathrm{animal}} + t_{\mathrm{dung}}\right) / n_{\mathrm{people}}$	hrs d^{-1}
t_{animal}	Total time spent each day by people in this group feeding, watering and herding animals	Input data	hrs d^{-1}
t_{dung}	Total time spent each day by people in this group managing dung	Input data	hrs d^{-1}
Time spent managing crops, t_{crop}			
t_{crop}	Time spent managing crops	$\left(t_{\mathrm{sow}} + t_{\mathrm{weed}} + t_{\mathrm{harv}}\right) / n_{\mathrm{people}}$	hrs d^{-1}
t_{sow}	Time spent sowing	Input data	hrs d^{-1}
t_{weed}	Time spent weeding	Input data	hrs d^{-1}
t_{harv}	Time spent harvesting	Input data	hrs d^{-1}
Time spent on other activities			
$t_{\mathrm{essential}}$	Time spent on essential activities	$t_{\mathrm{essential,i}} / n_{\mathrm{people}}$	hrs d^{-1}
$t_{\mathrm{essential,i}}$	Time spent on these activities by people in this group	Input data	hrs d^{-1}
$t_{\mathrm{non-essential}}$	Time available for non-	$t_{\mathrm{awake}} - t_{\mathrm{essential}}$	hrs d^{-1}

Symbol	Variable	Value, source or formula	Units
	essential activities		
t_{awake}	Time spent awake each day	Input data	hrs d^{-1}

2.8. Purchases and sales

Purchases and sales data are obtained directly from input data on the price of products and the amount purchased or sold for wet and dry seasons in a typical year. Entered values for sales are checked against the amount of products available within the household (Table 9).

Table 9

Purchases and sales. Note: Input data are shown in shaded cells.

Symbol	Variable	Value, source or formula	Units	Reference
Checks on products for sale				
Dung for sale, $M_{\mathrm{dung,sale}}$				
$M_{\mathrm{dung,sale}}$	Availability of dung for sale	$\sum_{cattle}\left(M_{\mathrm{dung,tot,typ}} \times {}^{P_{\mathrm{use,sale}}}/_{100}\right)$	kg y^{-1}	
$M_{\mathrm{dung,tot,typ}}$	Animal production in typical year of manure	Table 5		
$P_{\mathrm{use,sale}}$	Percentage of dung that is used for sale	Input data	%	
Checks on purchases				
N/A				

2.9. Model evaluation

The changes in SOC are a product of the other processes included in the model, being directly affected by crop production, nutrient turnover and soil water content, and indirectly affected by animal management, fuel use and labour availability. Therefore, comparison of simulated to measured values of SOC represents an integrated evaluation of many different aspects of the model, so the performance of the model was primarily evaluated here with respect to changes in SOC. Evaluations of simulated yield were also included to allow the sources of any errors to be better understood.

The evaluation was done using data collected on the long term experiment at the research farm of Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India (19°08′ N, 76°05′E), between 1983 and 2010 (Narkhede, 2019). The experiment used a sorghum-wheat cropping system, and was on a low organic C and alkaline silty clay loam (hyperthermic, Typic Haplustert (or Haplic Vertisol in World Reference Base); Soil Survey Division Staff, 1993) in a hot semi-arid eco-region (mean annual rainfall is 847mm, mean annual minimum and maximum temperatures are 10.5 and 41.6 ºC respectively). The measurements at this site provide a rare opportunity to evaluate the model against data from a well-controlled long-term experiment in a semi-arid environment. The data include detailed measurements of changes in SOC using a fully replicated and randomized trial that uses both inorganic and organic fertilisers, and rain-fed and irrigated conditions. Therefore, the trial allows the accuracy of simulations to be evaluated for changes in SOC in the different conditions that limit crop growth within the model (nutrients and water), and using different inputs of organic fertilisers.

The parameters used to describe sorghum and wheat were derived from independent data at other sites in India (Table 10). Parameters used to describe the organic fertiliser (partially composted farm yard manure; hereafter referred to as “compost”) were derived from measurements of C and N contents provided for the compost used at the site for 2009 – 2017 (ICAR, 2019) and using generic parameters for compost derived by Smith et al. (2014) (Table 11). The simulations were run from 1983 to 2010 using weather data recorded for the site as given in Fig. 2. At the start of the simulation, the soils were assumed to be in steady state with respect to the weather conditions for the first decade, and wheat and sorghum crops grown in rotation using the management practices as specified for 2009 – 2017 by ICAR (2019) (Table 12, Table 13). Unfortunately, the rates of fertiliser applications before 1983 are unknown. Therefore, the initialisation run also included adjustment of fertiliser applied in the years before the trial started to give the response of SOC to applied inorganic fertiliser observed in the treatment with 100% of the recommended N applied as inorganic fertiliser (treatment T5, Table 12). This amount of fertiliser was assumed to be applied to the sorghum and wheat crops in the pre-trial period in the same proportion as used in the trials. The yields of the pre-trial crops were assumed to differ from the yields in the first decade of T5 in proportion to the difference in the amount of fertiliser applied. In the subsequent evaluations against other treatments and in the application runs, this same rate of fertiliser was assumed to be applied during the pre-trial period. The SOC data used to set the pre-trial fertiliser applications (treatment with inorganic fertiliser at 100% of the recommended rate, T5) were excluded from the evaluation to maintain the independence of the evaluation. A more thoroughly independent evaluation would use no data from the site to set inputs, but was not possible at this site due to shortage of background information. However, the evaluation does allow the uncertainty in the simulations to be defined for this site and used in the subsequent applications.

The initialised model was run forwards using recorded weather and crop management data from the trial for 1983 to 2010 (Table 14). The simulations were evaluated using measurements of SOC to 15 cm depth (Table 15) and crop yield (Table 16), following the approach described by Smith et al. (1997) and by Smith and Smith (2007). In order to provide a simulation that is likely to be accurate in other sites with similar conditions, the simulations and measurements should show both high coincidence and high association (Smith and Smith, 2007). The association (similarity of trends) between the simulated values and the measurements was expressed using the Pearson’s correlation coefficient, with the significance of the correlation determined by a Student's *t*-test. The coincidence (closeness of fit) between the simulations and the measurements was quantified by calculating the root mean squared deviation of the simulations from the measurements; this was expressed both as the average total error (the average of the deviation of simulations from the measurements), and as a percentage of the mean measured value. The significance of the coincidence was determined by comparison to the values calculated for measurements at the 95% confidence interval from the mean using standard errors in the measurements for this trial; the standard errors in the SOC measurements were assumed to be ~1 t ha^{-1} from measurements on the same trial by Datta et al. (2018) and ~0.1 t ha^{-1} for crop yield from replicated measurements for 2011 – 2015 provided by ICAR (2019). The bias in the simulations was also calculated as the sum of the differences between simulations and measurements, and as a percentage of the mean measured value. Again, the significance of the bias was determined by comparison to the errors in the data presented for 2011 – 2015 by Datta et al. (2018) and ICAR (2019).

Table 10

Crop parameters for sorghum and wheat. Note: C = carbon, N = nitrogen.

Symbol	Variable	Units	Wheat Value	Wheat Source	Sorghum Value	Sorghum Source	Description of use
d_{max}	Maximum rooting depth	cm	120	(1)	90	(2)	Tables 2 & 4
$p_{\mathrm{C:N,plant}}$	C:N ratio of plant inputs		80	(3)	85	(4)	Table 3
N_{opt}	Amount of nitrogen required to achieve maximum yield	kg ha^{-1}	230	(3)	126	(4)	Table 4
N_{min}	Minimum amount of nitrogen that results in a harvestable yield	kg ha^{-1}	0	(3)	0	(4)	Table 4
c_{N}	Nitrogen response coefficient		0.6	(3)	1	(4)	Table 4
$M_{\mathrm{yld,max}}$	Maximum potential crop yield	t ha^{-1}	4.5	(3)	7.0	(4)	Table 4
I_{harv}	Harvest index		0.37	(5)	0.46	(5)	Table 1
$p_{\mathrm{PI:NPP}}$	Proportion of net primary production		0.2	(6)	0.2	(6)	Table 1

	incorporated in the soil			

Note: (1) Kirkegaard and Lilley (2007); (2) Hundal and De Datta (1984); (3) Mohanty (2015); Benbi et al. (1993) (4) Kushwah et al. (2013); Uchino et al. (2013) (5) Unkovich et al. (2010); (6) Bolinder et al. (2007)

Table 11

Parameters used to describe the organic fertiliser (partially composted farm yard manure). Note: C = carbon, N = nitrogen, DPM = decomposable plant material, HUM = humified soil organic matter, IOM = inert organic matter.

Symbol	Variable	Value	Source	Description of use
$p_{\mathrm{C:N,OW}}$	Average C:N ratio of organic waste	7.5	(1)	Table 3
$p_{\mathrm{NH4:N,OW}}$	Proportion of N in organic waste that is ammonium or urea	0.5	(1)	Table 3
$p_{\mathrm{D:H,OW}}$	Ratio of DPM:HUM in the active organic waste added	25	(2)	Table 1
$p_{\mathrm{IOM,OW}}$	Proportion of IOM in organic waste	0	(2)	Table 1
$p_{\mathrm{C,OW}}$	Proportion of C in organic waste	0.19	(1)	Table 1

Notes: (1) Experimental measurements from site; (2) Smith et al. (2014)

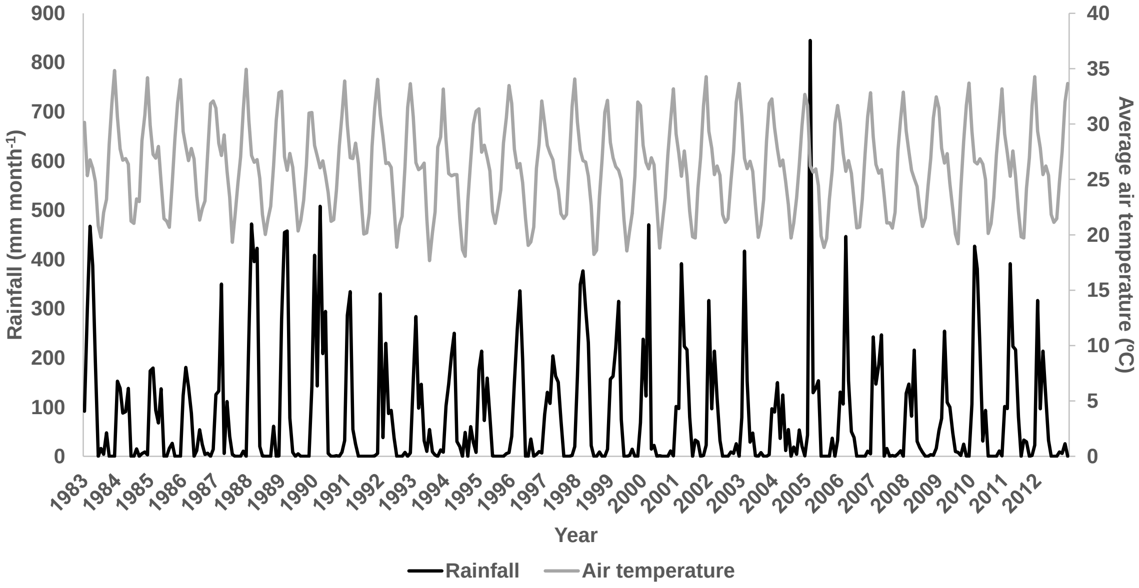


Fig. 2. Weather data from Parbhani, Maharashtra, India, used to drive the simulations

Table 12

Soil data used to initialise simulations at Parbhani, Maharashtra, India. Note EC 1:5 = electrical conductivity in 1:5 soil-water extract by volume.

Soil characteristics used to initialise soil organic matter pools		Measurements from treatment with 100% recommended rate of N applied as inorganic fertiliser (T5); used to set pre-trial fertiliser application rates	
Initial soil characteristics	Value	Year	Soil organic carbon (t ha^{-1})
Soil depth (cm)	15	1983-84	12.0
Clay content (g per 100 g soil)	30	1988-89	12.9
Silt content (g per 100 g soil)	30.7	1991-92	14.5
Sand content (g per 100 g soil)	39.3	1998-99	13.5
Carbon content (g per 100 g soil)	0.667	2002-03	14.4
Soil bulk density (g cm^{-3})	1.19	2005-06	14.6
Soil pH	8.32	2009-10	14.9
Soil salinity (EC 1:5)	0.37		

Table 13

Crop data used to initialise simulations using 100% of the recommended nitrogen application rate as inorganic fertiliser at Parbhani, Maharashtra, India. Note: N = nitrogen.

				Chemical fertiliser N		
Crop	Sowing	Harvest	Yield (t ha^{-1})	Amount (kg ha^{-1})	Application month	Irrigation (mm)
Sorghum	Jul-83	Oct-83	1.65	80	Jul-83	0
Wheat	Nov-83	Mar-84	1.66	100	Nov-83	480
Sorghum	Jul-84	Oct-84	3.83	80	Jul-84	0
Wheat	Nov-84	Mar-85	1.91	100	Nov-84	480
Sorghum	Jul-85	Oct-85	5.01	80	Jul-85	0
Wheat	Nov-85	Mar-86	2.42	100	Nov-85	480
Sorghum	Jul-86	Oct-86	3.75	80	Jul-86	0
Wheat	Nov-86	Mar-87	2.42	100	Nov-86	480
Sorghum	Jul-87	Oct-87	3.38	80	Jul-87	0
Wheat	Nov-87	Mar-88	3.26	100	Nov-87	480
Sorghum	Jul-88	Oct-88	1.26	80	Jul-88	0
Wheat	Nov-88	Mar-89	3.54	100	Nov-88	480
Sorghum	Jul-89	Oct-89	2.65	80	Jul-89	0
Wheat	Nov-89	Mar-90	3.04	100	Nov-89	480
Sorghum	Jul-90	Oct-90	3.94	80	Jul-90	0
Wheat	Nov-90	Mar-91	3.94	100	Nov-90	480
Sorghum	Jul-91	Oct-91	5.15	80	Jul-91	0
Wheat	Nov-91	Mar-92	4.11	100	Nov-91	480
Sorghum	Jul-92	Oct-92	3.43	80	Jul-92	0
Wheat	Nov-92	Mar-93	2.86	100	Nov-92	480

Table 14

Crop management data used to drive simulations to evaluate ORATOR from 1983 to 2010 at Parbhani, Maharashtra, India. Note: N = nitrogen; “compost” = partially composted farmyard manure.

Treatments		Percentage of recommended N rate applied					
Crop	Fertiliser type	T1	T2	T3	T4	T6	T7
Sorghum	Inorganic	0%	50%	100%	75%	100%	75%
	Organic	0%	0%	0%	0%	0%	0%
Wheat	Inorganic	0%	50%	50%	75%	50%	75%
	Organic	0%	0%	0%	0%	50%	25%
Sorghum	Applied N	July					
	Inorganic (kg ha^{-1})	0	40	80	60	80	60
	Sowing	July					
	Harvest	October					
	Irrigation (mm)	0					
Wheat	Applied N (kg ha^{-1})	November					
	Inorganic (kg ha^{-1})	0	40	40	60	40	60
	Organic (kg ha^{-1})	0	0	0	0	40	20
	Fresh weight amount of compost applied (t ha^{-1})	0	0	0	0	2	1
	Sowing	November					
	Harvest	March					
	Irrigation (mm)	480					

Table 15

Soil organic carbon measurements used to evaluate model performance at Parbhani, Maharashtra, India. Note: N = nitrogen.

	Treatments	Percentage of recommended N rate applied					
Crop	Fertiliser type	T1	T2	T3	T4	T6	T7
Sorghum	Inorganic	0%	50%	100%	75%	100%	75%
	Organic	0%	0%	0%	0%	0%	0%
Wheat	Inorganic	0%	50%	50%	75%	50%	75%
	Organic	0%	0%	0%	0%	50%	25%
	Year	Soil organic carbon (t ha^{-1})					
	1983-84	11.91	12.11	12.11	11.91	12.01	12.01
	1988-89	11.72	12.08	12.28	12.22	16.22	16.14
	1991-92	14.61	14.42	14.54	14.76	14.21	17.14
	1998-99	11.11	12.89	13.29	13.45	15.49	15.33
	2002-03	10.76	12.04	12.46	12.60	14.62	14.30
	2005-06	11.02	12.19	12.69	12.78	14.79	14.45
	2009-10	11.75	12.72	12.71	13.00	15.86	14.77

Table 16

Crop yield measurements used to evaluate model performance at Parbhani, Maharashtra, India. Note: N = nitrogen.

Treatments		Percentage of recommended N rate applied					
Crop	Fertiliser type	T1	T2	T3	T4	T6	T7
Sorghum	Inorganic	0%	50%	100%	75%	100%	75%
	Organic	0%	0%	0%	0%	0%	0%
Wheat	Inorganic	0%	50%	50%	75%	50%	75%
	Organic	0%	0%	0%	0%	50%	25%
Crop	Harvest	Yield (t ha^{-1})					
Sorghum	Oct-83	0.10	0.90	0.76	1.42	0.92	1.45
Wheat	Mar-84	0.56	1.33	1.44	1.55	1.82	1.54
Sorghum	Oct-84	0.74	2.41	2.81	3.14	3.27	3.86
Wheat	Mar-85	0.89	1.54	1.77	1.69	2.04	1.77
Sorghum	Oct-85	0.69	2.94	3.52	3.65	4.71	4.79
Wheat	Mar-86	0.88	1.74	2.00	1.94	2.49	2.20
Sorghum	Oct-86	0.54	2.33	3.19	3.55	4.37	4.29
Wheat	Mar-87	0.98	2.00	2.39	2.26	2.63	2.41
Sorghum	Oct-87	0.81	2.39	2.48	3.01	3.65	3.60
Wheat	Mar-88	1.26	2.12	2.48	2.30	3.74	3.17
Sorghum	Oct-88	0.10	0.73	0.86	0.99	1.43	1.24
Wheat	Mar-89	1.14	1.99	2.45	2.56	3.51	3.42
Sorghum	Oct-89	0.25	1.73	1.76	2.22	3.09	2.44
Wheat	Mar-90	0.95	2.16	2.42	2.56	3.07	2.97
Sorghum	Oct-90	0.55	2.75	3.01	3.42	4.23	4.06
Wheat	Mar-91	0.78	2.66	2.87	3.56	3.70	3.85
Sorghum	Oct-91	0.56	3.18	3.33	4.08	4.94	5.09
Wheat	Mar-92	0.63	2.13	3.10	2.60	3.99	3.92
Sorghum	Oct-92	0.35	1.45	2.02	3.33	3.65	3.51
Wheat	Mar-93	0.99	2.43	2.41	2.48	3.01	2.96
Sorghum	Oct-93	0.58	4.10	4.27	4.25	5.08	4.89
Wheat	Mar-94	0.62	1.34	1.81	1.69	2.13	1.85
Sorghum	Oct-94	0.27	1.85	2.25	2.33	2.68	2.79
Wheat	Mar-95	0.66	1.53	1.66	1.57	1.89	1.75
Sorghum	Oct-95	0.33	1.87	2.08	1.89	1.57	2.54
Wheat	Mar-96	0.79	1.24	1.58	1.68	2.15	2.13
Sorghum	Oct-96	No measurements					
Wheat	Mar-97	0.14	0.75	1.10	0.95	1.35	1.19
Sorghum	Oct-97	0.29	1.75	2.12	2.08	2.75	2.60
Wheat	Mar-98	0.58	1.22	2.01	1.73	2.28	1.92
Sorghum	Oct-98	0.00	0.80	1.14	1.04	1.49	1.32
Wheat	Mar-99	0.43	1.36	1.99	1.78	2.21	1.62
Sorghum	Oct-99	0.42	2.38	3.23	3.06	3.64	3.39
Wheat	Mar-00	0.34	1.22	2.00	2.12	2.59	2.48
Sorghum	Oct-00	0.00	0.99	1.45	1.60	2.23	2.13

Wheat	Mar-01	0.34	1.06	1.21	1.44	2.28	1.93
Sorghum	Oct-01	0.94	5.16	5.28	5.58	5.96	5.66
Wheat	Mar-02	0.27	1.67	1.87	1.92	2.96	2.43
Sorghum	Oct-02	0.84	3.26	3.18	3.34	3.88	3.67
Wheat	Mar-03	0.18	1.23	1.72	1.65	2.33	2.05
Sorghum	Oct-03	0.00	2.02	2.14	2.30	2.59	2.19
Wheat	Mar-04	0.95	2.21	2.26	2.47	2.50	2.51
Sorghum	Oct-04	0.63	2.84	3.37	3.57	4.20	3.95
Wheat	Mar-05	0.06	1.79	1.88	1.94	2.12	2.13
Sorghum	Oct-05	0.04	0.88	0.70	0.83	1.58	1.33
Wheat	Mar-06	0.33	1.50	1.74	2.12	2.07	1.19
Sorghum	Oct-06	0.00	1.29	1.65	1.52	2.22	1.98
Wheat	Mar-07	0.49	2.03	2.36	2.63	3.29	2.72
Sorghum	Oct-07	0.36	1.70	1.82	1.83	2.99	3.06
Wheat	Mar-08	0.41	1.96	2.25	2.29	2.83	2.56
Sorghum	Oct-08	0.12	1.90	1.87	2.23	2.43	2.20
Wheat	Mar-09	0.44	1.98	2.16	2.34	2.71	2.48
Sorghum	Oct-09	0.12	1.22	1.32	1.47	1.89	1.66
Wheat	Mar-10	0.37	2.11	2.10	2.45	3.20	2.54
Sorghum	Oct-10	0.16	1.83	2.08	2.25	2.72	2.42

2.10. Model application

To demonstrate potential applications of the model, ORATOR was used to assess the impact of applying N as inorganic fertiliser, compost or a combination of inorganic fertiliser and compost on the resources available to households in Parbhani, Maharashtra, India. The model was run for the simplified case where the household grows exclusively wheat and sorghum in rotation and (a) does not use manure for fuel, or (b) currently uses all of the manure that would be required for soil incorporation as fuel. The simulations were used to estimate the overall impact of the different sources of N on yield and net farm income, C sequestration, soil water, and soil N supply and N use efficiency. The options considered were 100% inorganic fertiliser, 50% inorganic and 50% organic fertiliser, and 100% organic fertiliser. The characteristics of the organic fertiliser used were set to be equivalent to the compost used in the trials (Table 11). The selection of 50:50 inorganic to organic fertiliser was used to illustrate the impact of integrating inorganic and organic fertiliser use. These proportions could also have been adjusted to assess the impact on the soils, crops and household of different combinations of fertiliser sources. However, this was not done here.

To capture the relevant changes in net farm income for this simplified example, the contribution to net farm income of the different crop management options considered, I_{farm} (US\$), was calculated from the amount and maximum market value of (a) grain produced, M_{yld} (t ha^{-1}) and v_{yld} (US\$ t^{-1}), (b) fertiliser use, M_{fert} (kg ha^{-1}) and v_{fert} (US\$ kg^{-1}), and (c) liquefied petroleum gas (LPG) fuel required to replace the dung used as fuel, $M_{\mathrm{dung}\rightarrow\mathrm{fert}}$ (t ha^{-1}) and $v_{\mathrm{dung}\rightarrow\mathrm{LPG}}$ (US\$ t^{-1}),

$$I_{\mathrm{farm}} = \left(M_{\mathrm{yld}} \times v_{\mathrm{yld}}\right) - \left(M_{\mathrm{fert}} \times v_{\mathrm{fert}}\right) - \left(M_{\mathrm{dung}\rightarrow\mathrm{fert}} \times v_{\mathrm{dung}\rightarrow\mathrm{LPG}}\right).$$

The market prices for grain and urea fertiliser that were used are given in Table 17. The prices for wheat and sorghum were assumed to be fixed at the maximum market price provided by the farmer’s portal for Parbhani, Maharashtra for March 2019 (Farmer’s Portal, 2019), 23.38 INR kg^{-1} (v_{yld} = 338 US\$ t^{-1}) for wheat and 30.27 INR kg^{-1} (v_{yld} = 438 US\$ t^{-1}) for sorghum (assuming an exchange rate of 0.014457 US\$ per INR, Currency converter, 2019). The cost of N fertiliser was assumed to be fixed at the price given on the Tamil Nadu Agricultural University website, updated 21 May 2013 (TNAU, 2013); mode = 276, range = (265 – 278) INR for a 50 kg bag of urea fertiliser containing 46% N. This is equivalent to an average price of 12.0 (±0.6) INR per kg of N fertiliser, or v_{fert} = 0.17 (±0.01) US\$ kg^{-1}. The cost of replacing dung with LPG (51.12 Indian Rupees (INR) per kg) was obtained from the price given for LPG for March 2019 (Good Returns, 2019a). The amount of replacement fuel needed was determined from the net calorific values of dung and LPG, and stove efficiencies, giving a cost of replacing dung with LPG of 2005 INR t^{-1} (Table 18) ($v_{\text{dung}\rightarrow\text{LPG}}$ = 28.99 US\$ t^{-1}).

The longer term impacts of the different treatments on C sequestration and on water and N use efficiency were simulated by assuming weather conditions from 2013 to 2082 are unchanged from 2003 to 2012, and then running the model forwards for another 70 years (100 year total simulation). The impacts of climate change could have been considered by using projected climate data, but this was not done in this example application. A 3rd order parabolic trendline was fitted to the simulated change in SOC from the start of the simulation in order to determine the trend in C change. The change in soil water was calculated by comparison to the water content in the control. The N use efficiency was calculated from the ratio of the average annual yield to inorganic plus organic fertiliser N application.

Table 17

Assumed price of urea and grain at Parbhani, Maharashtra, India. Note: NFCL and SPIC are referred to in TNAU (2013); NPK fertiliser is inorganic fertiliser containing combined nitrogen, phosphorus and potassium in proportions specified; INR = Indian Rupees; prices are assumed to be fixed at the rates given as more dynamic pricing is overly complex for the analysis presented here.

		Source
Maximum price = 10:26:26 NPK fertiliser from NFCL (INR kg^{-1})	1111.25	(1)
Minimum price = 20:20:20 NPK fertiliser from SPIC (INR kg^{-1})	87.78	(1)
Typical price of urea fertiliser (INR kg^{-1} N)	12.0	(1)
Range in price of urea fertiliser (INR kg^{-1} N)	0.6	(1)
Maximum market price of wheat (INR kg^{-1})	23.38	(2)
Maximum market price of sorghum (INR kg^{-1})	30.27	(2)
Note: (1) TNAU (2013); (2) Farmer’s Portal (2019)		

Table 18

Cost of replacing dung with liquefied petroleum gas (LPG) at Parbhani, Maharashtra, India. Note INR = Indian Rupees.

Symbol / Formula	Variable	Dung	Source	LPG	Source
H_{cal}	Net calorific value (MJ kg^{-1})	11.9	(1)	45.24	(1)
$\varepsilon_{\text{stove}}$	Stove efficiency (%)	8.5	(1)	57	(1)

$\epsilon_{\text{cook}} = H_{\text{cal}} \times \varepsilon_{\text{stove}}$	Cooking value (MJ kg^{-1})	1.0	25.8	
v_{LPG}	Maximum market price (INR kg^{-1})		51.12	(2)
$v_{\text{dung}\rightarrow\text{LPG}} = v_{\text{LPG}} \times {}^{\epsilon_{\text{cook,dung}}}/_{\epsilon_{\text{cook,LPG}}}$	Cost of replacing dung with LPG, (INR t^{-1})		2005	

Note: Singh et al. (2014); (2) Good Returns (2019a).

3. Results and discussion

3.1. Initialisation and determination of pre-trial fertiliser inputs

The best fit between the simulations and measurements in the inorganic fertiliser plots was obtained if typical fertiliser applications during the pre-trial period were 40% of the fertiliser rate used in the trials (Fig. 3); this equates to a typical application rate of 32 kg ha^{-1} y^{-1} for sorghum and 40 kg ha^{-1} y^{-1} for wheat. When initialised using this rate of fertiliser application to steady state at the SOC measured at the start of the trial (11.89 t ha^{-1} in the top 15 cm), the soils contained 0.05% as DPM, 15% as RPM, 2.45% as BIO, 76% as HUM and 6.9% as IOM (Fig. 4).

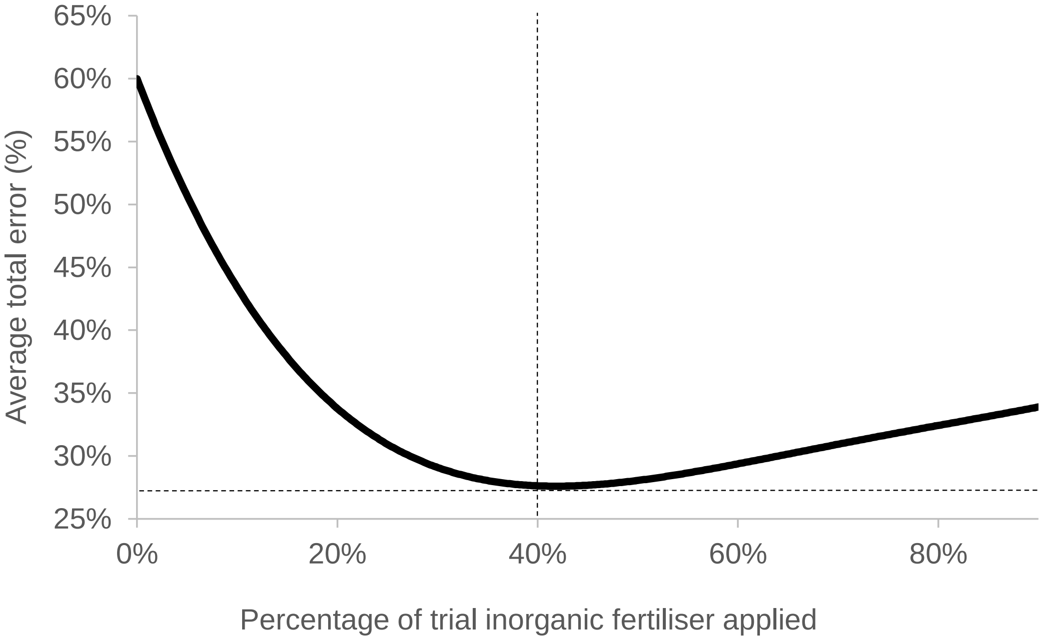
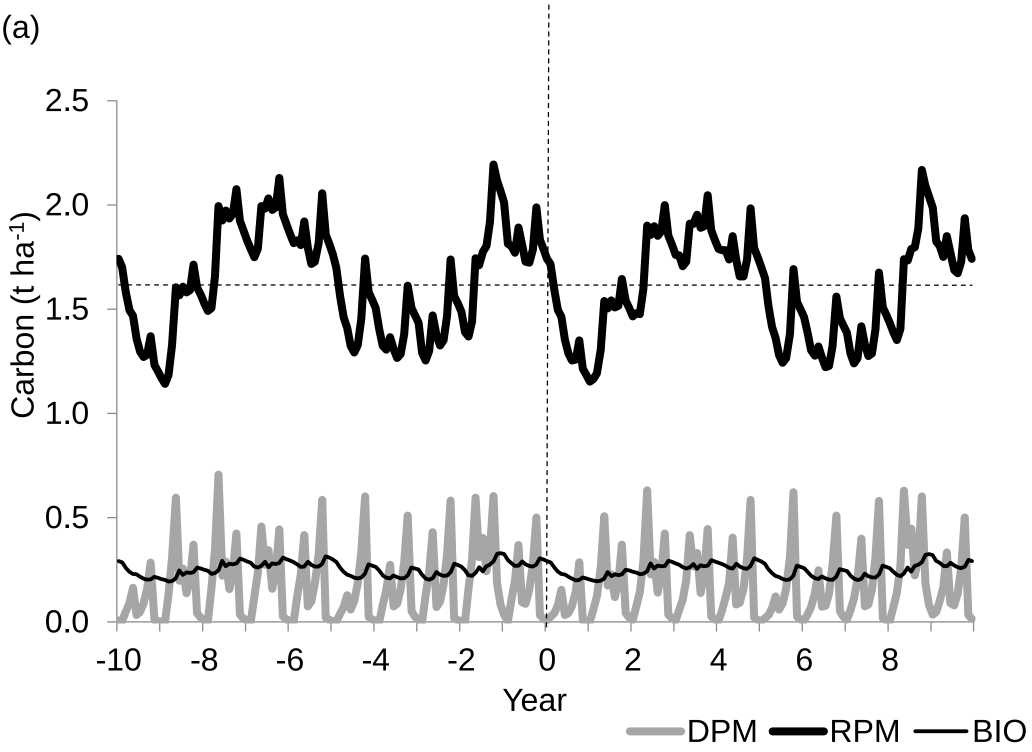


Fig. 3. Change in average total error between simulated and measured soil organic carbon in inorganic fertiliser trial with adjustment of fertiliser inputs before the trial started



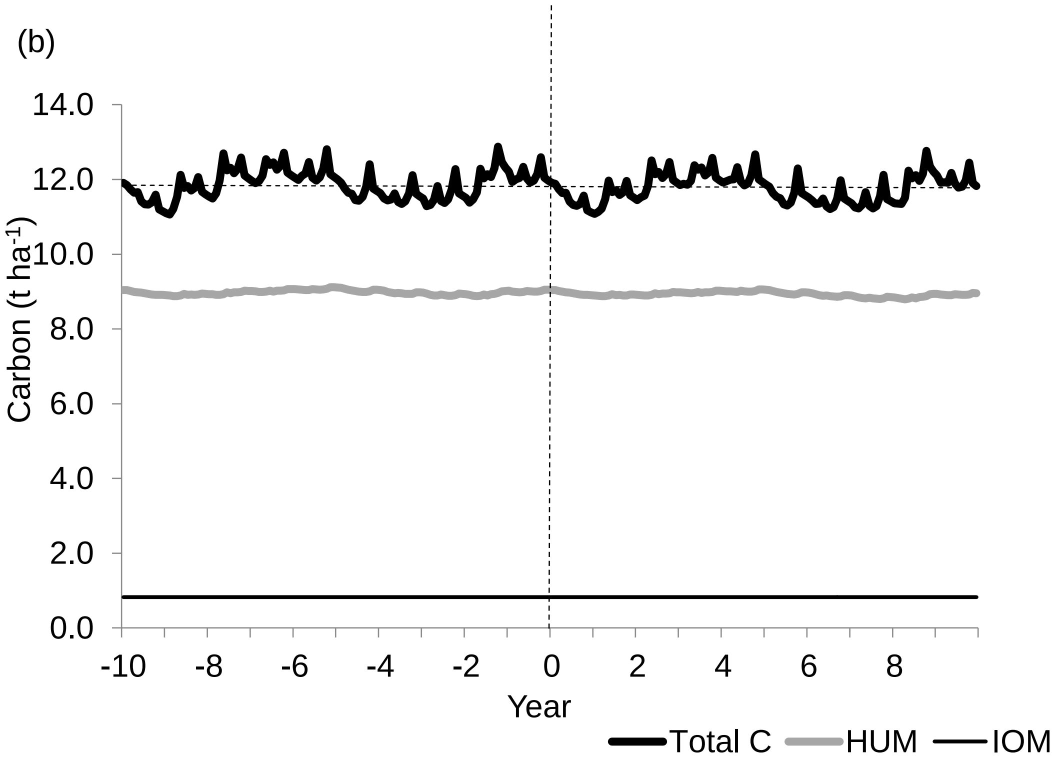


Fig. 4. Soil organic carbon pools initialised to be at steady state at the carbon content measured at the start of the trail (11.89 t ha^{-1} in the top 15 cm) and assuming 35% of the fertiliser used in inorganic fertiliser trial at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, (a) active carbon pools, decomposable plant material (DPM), resistant plant material (RPM) and biomass (BIO), (b) passive carbon pools, humus (HUM), inert organic matter (IOM).

3.2. Evaluation of model performance

3.2.1. Crop yields

There was a significant correlation ($p < 0.05$) between the independent measured crop yields (Table 16) and the simulations in the different treatments across all crops, and across sorghum and wheat separately (Table 19 and Fig. 5). The average error over all crops was 0.90 t ha^{-1}, equivalent to 43% of the average crop yield with a crop value of 351 US$ ha^{-1}; for sorghum the average error was 1.09 t ha^{-1} (48%) with a value of 479 US$ ha^{-1}, while for wheat it was 0.71 t ha^{-1} (38%) with a value of 242 US$ ha^{-1}. This was outside the assumed average experimental error of 0.80 t ha^{-1} (38%; 310 US$ ha^{-1}), so improved simulations could have provided a better representation of the measurements. However, the bias in the simulations was an over-estimate of yield over all crops by an average of only 0.44 t ha^{-1} (21%; 169 US$ ha^{-1}); for sorghum this was 0.47 t ha^{-1} (21%; 204 US$ ha^{-1}), while for wheat it was 0.41 t ha^{-1} (21%; 138 US$ ha^{-1}), so similar bias was observed in both crops, and this was within experimental error. As shown in Fig. 6, the measured crop yields were consistently lower than the simulations in all treatments between 1995 and 2000, perhaps reflecting some other nutrient deficiency, pest attack or disease outbreak that occurred during that time, which would not have been simulated by the model because the version presented here only accounts for the impacts of N and weather conditions on yield. However, although the percentage error is relatively high, because the yield difference is small (less than 1 t ha^{-1}) and only up to 20% of the net primary production is incorporated into the soil (Table 10), this is expected to introduce a maximum annual bias of only 0.21 t ha^{-1} y^{-1} to the plant C inputs to the soil, equivalent to only 16% of the compost inputs used in the application of the model (Table 20). Therefore, this error in estimated crop yield is not likely to introduce a significant change in the results of the application of the model. In the subsequent applications of the model it was assumed that the error in crop yield was 1.09 t ha^{-1} for sorghum and 0.71 t ha^{-1} for wheat, with an associated bias of 0.47 and 0.41 t ha^{-1}, respectively.

Table 19

Statistical evaluation of the simulation of crop yields at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, between 1983 and 2010. Treatments include (T1) control – no nitrogen applied, (T2) 50% recommended nitrogen fertiliser applied to sorghum and wheat, (T3) 100% applied to sorghum and 50% applied to wheat, (T4) 75% recommended nitrogen fertiliser applied to sorghum and wheat, (T6) 100% applied to sorghum and 50% inorganic plus 50% organic fertiliser applied to wheat, and (T7) 75% applied to sorghum and 75% inorganic plus 25% organic fertiliser applied to wheat.

	Experimental error	All crops	Sorghum	Wheat
ASSOCIATION				

Pearson's correlation coefficient		0.57	0.57	0.53
p-value		0.00	0.00	0.00
COINCIDENCE				
Root mean squared deviation				
Average total error (t ha^{-1})	0.80	0.90	1.09	0.71
(INR ha^{-1})	21460	24257	33108	16711
(US$ ha^{-1})	310	351	479	242
Percentage of mean measured value (%)	38%	43%	48%	38%
BIAS		0.00	0.00	0.00
Average bias (t ha^{-1})		0.44	0.47	0.41
(INR ha^{-1})		11706	14100	9514
(US$ ha^{-1})		169	204	138
Relative error (%)		21%	21%	21%

Note: [a] Assumed 1 INR = 0.0144482 US$ (XE Currency converter - https://www.xe.com/currencyconverter/)

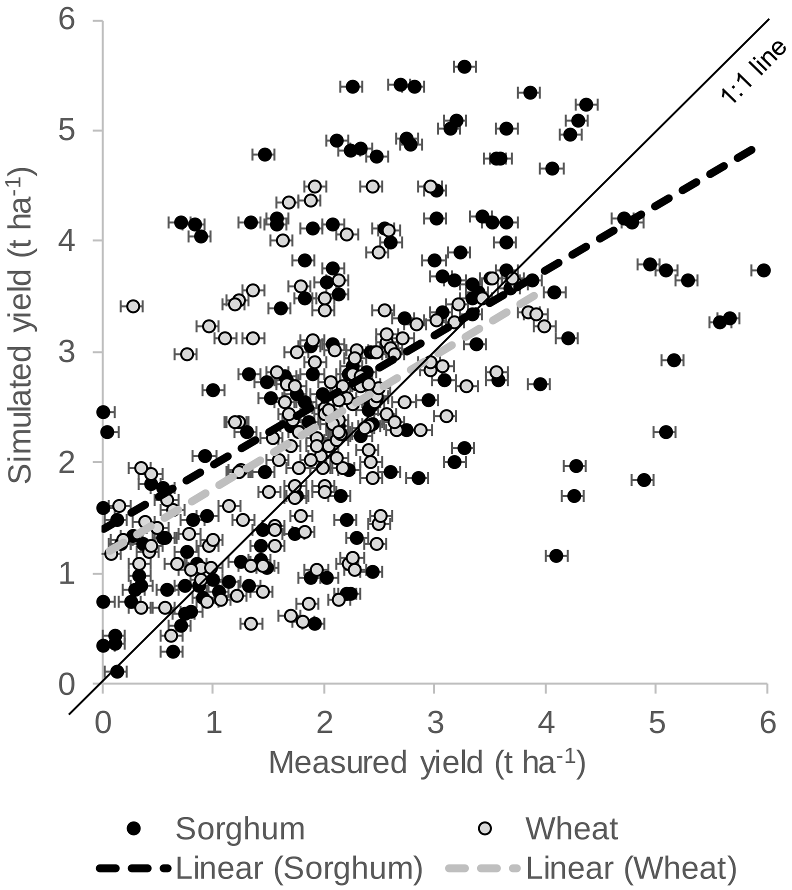
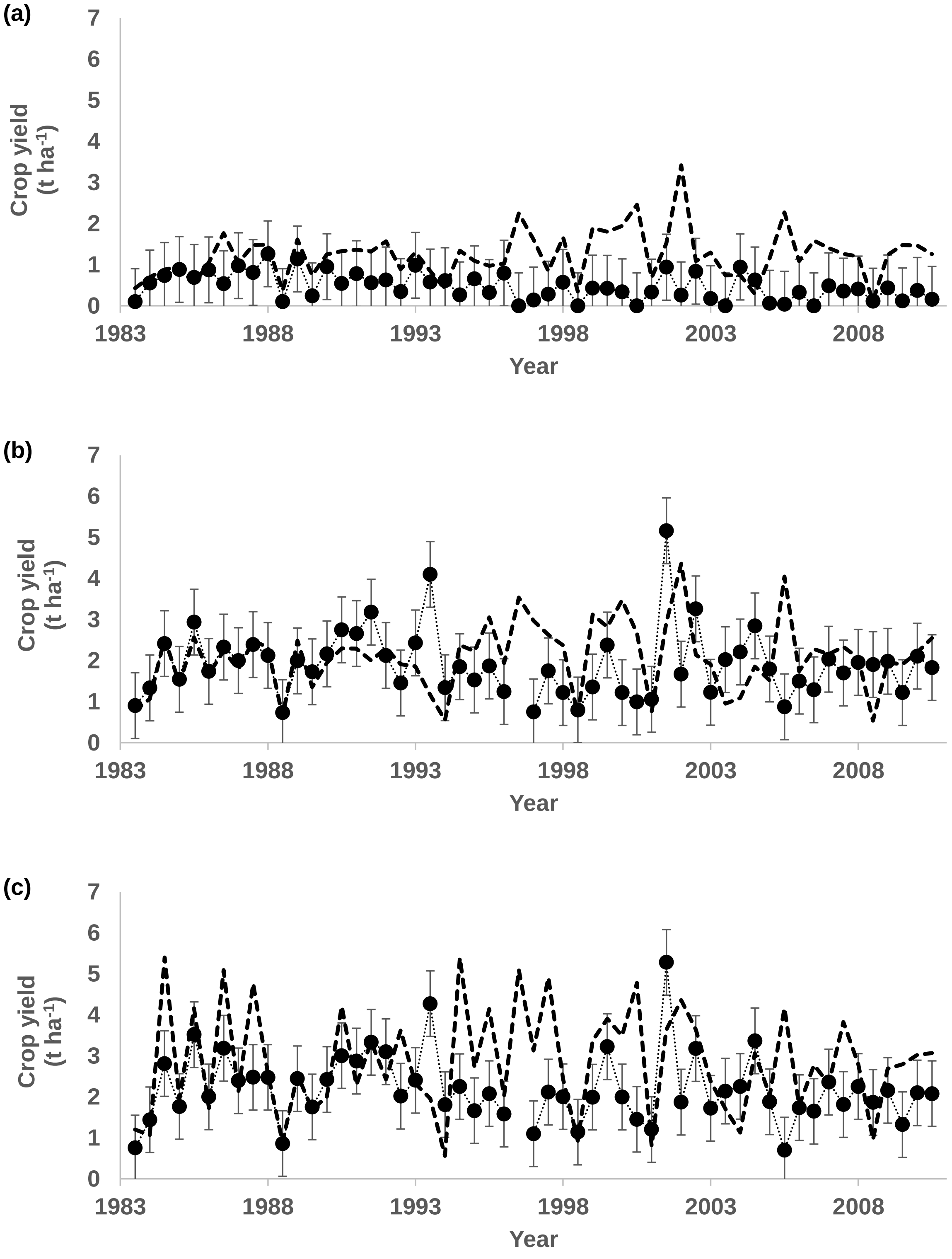


Fig. 5. Simulated vs measured crop yields at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, between 1983 and 2010. Treatments include (T1) control – no nitrogen applied, (T2) 50% recommended nitrogen fertiliser applied to sorghum and wheat, (T3) 100% applied to sorghum and 50% applied to wheat, (T4) 75% recommended nitrogen fertiliser applied to sorghum and wheat, (T6) 100% applied to sorghum and 50% inorganic plus 50% organic fertiliser applied to wheat, and (T7) 75% applied to sorghum and 75%

inorganic plus 25% organic fertiliser applied to wheat. Note, error bars represent the standard errors observed in trials of ~0.1 t ha^{-1} from 2011 – 2015 in ICAR (2019).



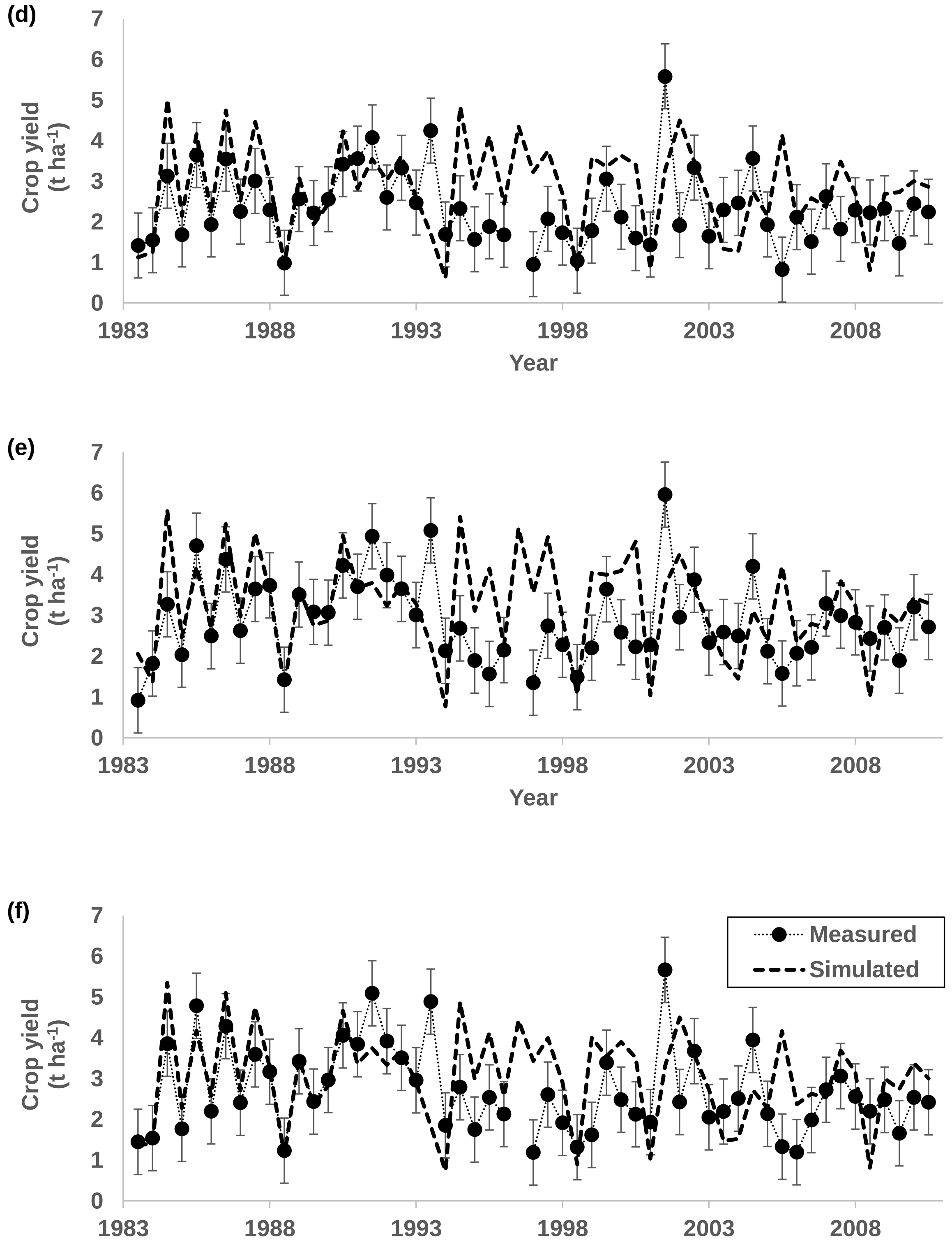


Fig. 6. Comparison of simulated and measured crop yields at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, between 1983 and 2010. (a) T1- control – no nitrogen applied, (b) T2 - 50% recommended nitrogen fertiliser applied to sorghum and wheat, (c) T3 - 100% applied to sorghum and 50% applied to wheat, (d) T4 - 75% recommended nitrogen fertiliser applied to sorghum and wheat, (e) T6 - 100% applied to sorghum and 50% inorganic plus 50% organic fertiliser applied to wheat, and (f) T7 - 75%

applied to sorghum and 75% inorganic plus 25% organic fertiliser applied to wheat. Note, error bars represent the average 95% confidence interval observed in trials of 0.8 t ha^{-1} from 2011 – 2015 in ICAR (2019).

Table 20

Expected impact of errors in yield estimates on the application of the model to long term changes in simulated soil organic carbon at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India.

Symbol / formula	Variable	Overall	Sorghum	Wheat	Source
I_{harv}	Harvest index		0.37	0.46	Table 10
$p_{\text{PI:NPP}}$	Proportion of net primary production incorporated in the soil		0.2	0.2	Table 10
e_{yld}	Average bias in yield (t ha^{-1})	0.44	0.47	0.41	Table 19
$e_{\text{npp}} = {e_{\text{yld}}}/{I_{\text{harv}}}$	Average bias in net primary production (t ha^{-1})	1.07	1.26	0.88	
$e_{\text{PI}} = p_{\text{PI:NPP}} \times e_{\text{npp}}$	Max. annual bias in plant C inputs to soil due to yield bias (t ha^{-1})	0.21			
$p_{\text{C:N,OW}}$	Average C:N ratio of organic waste	7.5			Table 11
N_{rec}	Recommended N application rate (kg ha^{-1})		80	100	Table 13
$C_{\text{OW}} = \frac{N_{\text{rec}} \times p_{\text{C:N,OW}}}{1000}$	C input with compost equivalent of 100% recommended N (t ha^{-1})	1.35	0.6	0.75	
${e_{\text{PI}}}/{C_{\text{OW}}}$	Ratio of max. annual bias to compost inputs	0.16			

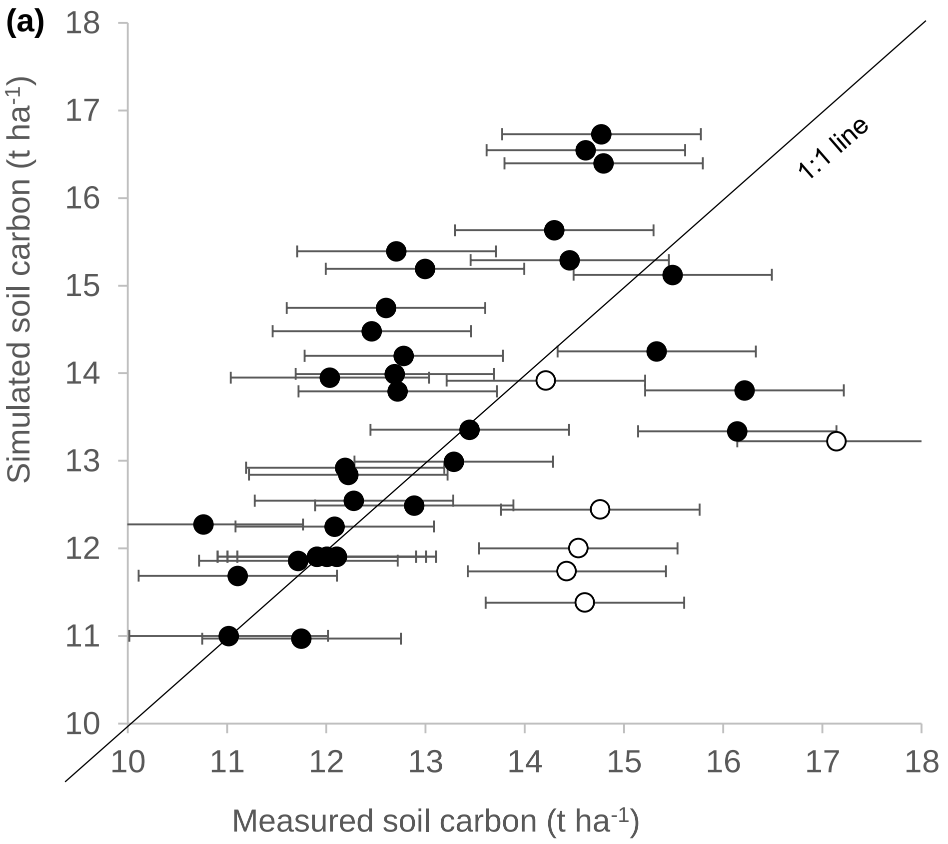
3.2.2. Soil organic carbon

There were less data available for evaluation of the simulations of SOC than for yield. Therefore, although the correlation coefficient over all trials was relatively high (0.51 compared to 0.57 for crop yield), it was non-significant (Table 21; Fig. 7). As can be seen in Fig. 8, this is mainly attributable to unusually high values in most treatments of measured soil organic C in 1991/92; if these values were to be excluded, the correlation would become significant, but there was no rational basis for doing this, so it was not done (Table 21). The average error in simulated SOC was 1.25 t ha^{-1} (9% of the average measured SOC); this is less than the 95% confidence interval in the experimental error (standard error ~1 t ha^{-1}; 95% confidence for 40 degrees of freedom is 2 t ha^{-1}), so simulations within experimental error. The bias was also low; -0.11 t ha^{-1} (1% of the total C and 9% of the change in SOC) (Fig. 7 and Fig. 8). In the subsequent applications, it was assumed that the average error in simulated SOC was 1.25 t ha^{-1} with a bias of -0.11 t ha^{-1}.

Table 21

Statistical evaluation of the simulation of soil organic carbon at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, between 1983 and 2010. Treatments include control, inorganic fertiliser, and inorganic fertiliser plus compost. Bold font indicates a non-significant correlation.

Treatments	Experimental error	All trials	All trials excluding 91/92
ASSOCIATION			
Pearson's correlation coeff.		0.51	0.72
p-value		**0.65**	0.01
COINCIDENCE			
Root mean squared deviation			
Average total error (t ha^{-1})	2.02	1.25	0.89
Percentage of average measured carbon (%)	15%	9%	7%
BIAS			
Average bias (t ha^{-1})		-0.11	-0.52
Relative error			
% of average carbon measurement		1%	-68%
% of ave. change in measured carbon		9%	-40%


(a)
Simulated soil carbon (t ha-1)
Measured soil carbon (t ha-1)
1:1 line
10
11
12
13
14
15
16
17
18

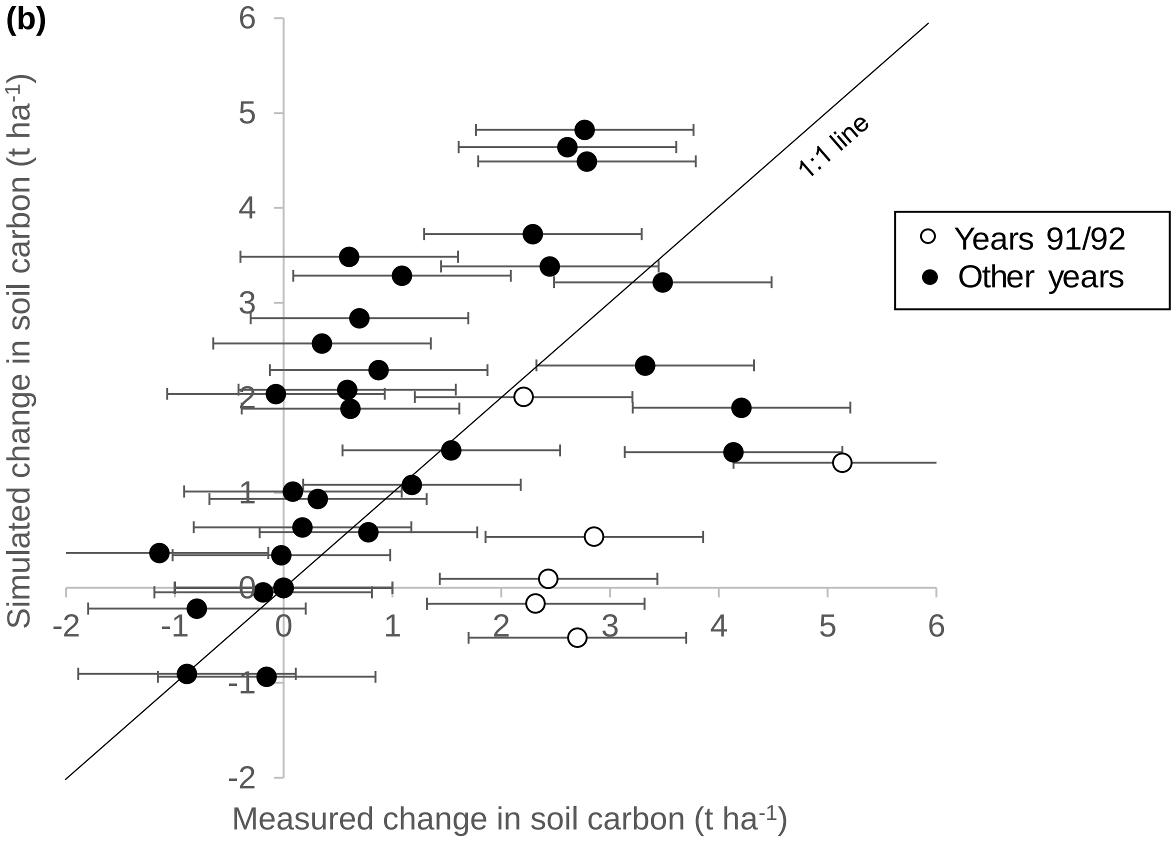
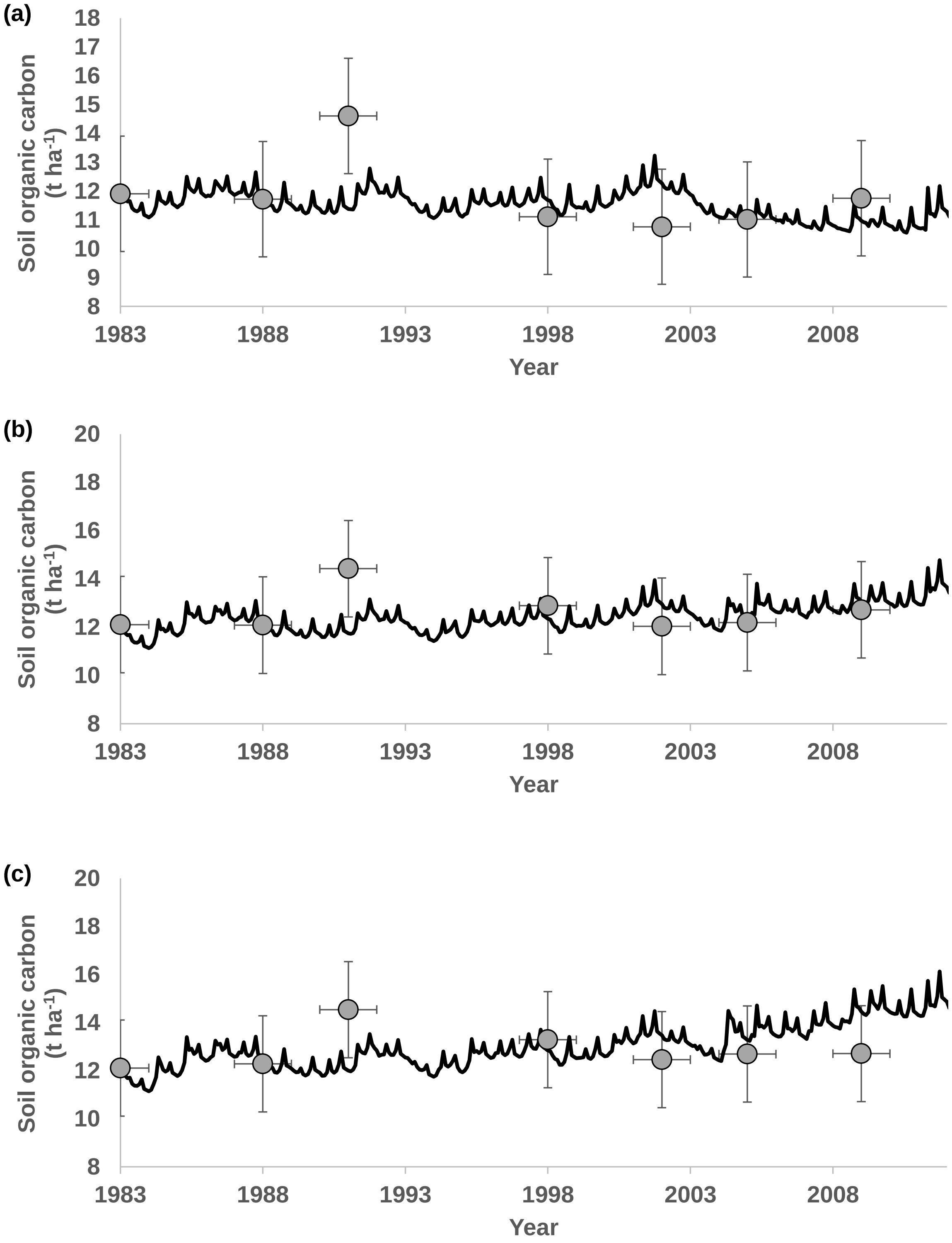

(b)
Simulated change in soil carbon (t ha-1)
Measured change in soil carbon (t ha-1)
1:1 line
○ Years 91/92
● Other years
-2
-1
0
1
2
3
4
5
6

Fig. 7. Simulated vs measured soil organic carbon at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, between 1983 and 2010. (a) Total organic carbon; (b) Change in organic carbon since the start of the trial. Note error bars shows the typical standard errors (~1 t ha^{-1}) observed by Datta et al (2018) at the same site; unfilled points indicate measured values for 1991-92.



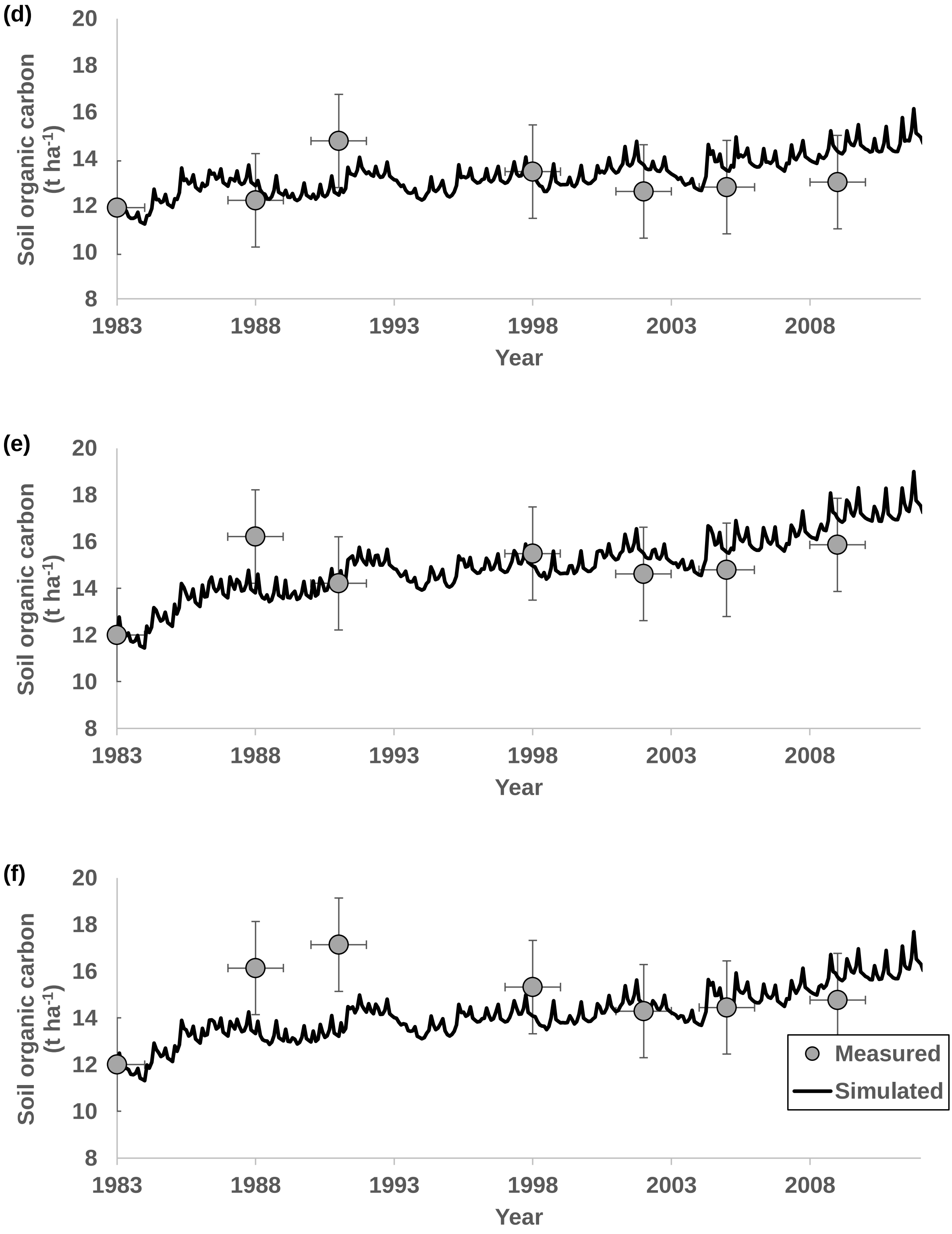


Fig. 8. Comparison of simulated and measured soil organic carbon at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, between 1983 and 2010. (a) T1- control – no nitrogen applied, (b) T2 - 50% recommended nitrogen fertiliser applied to sorghum and wheat, (c) T3 - 100% applied to sorghum and 50% applied to wheat, (d) T4 - 75% recommended nitrogen fertiliser applied to sorghum and wheat, (e) T6 - 100% applied to sorghum and 50% inorganic plus 50% organic fertiliser applied to wheat, and (f) T7 - 75% applied to sorghum and 75% inorganic plus 25% organic fertiliser applied to wheat. Note:

horizontal error bars show the uncertainty in the time of measurement; vertical error bars shows the typical confidence intervals (~2 t ha^{-1}) observed by Datta et al (2018) at the same site.

3.2.3. Wider implications of the evaluation

Because this is a process-based model, given local field trials for crop parameterisation, it should (in theory) be equally accurate in other conditions. In practice, the model has, of course, not been tested in conditions that are not found in this part of India (e.g. freezing / thawing or extreme wetting / drying). We would expect to see larger errors if the environmental conditions result in increased importance of any processes that are not adequately described in the model. Therefore, while we can be confident that the evaluation provides an estimate of the accuracy of the model in the semi-arid conditions of Maharashtra, further testing would be required to provide evidence of the model accuracy in cooler or wetter regions. Further testing of the model at a wider range of sites is always valuable and will provide a more complete picture of (a) the accuracy to be expected in the model in different locations and (b) the processes that are inadequately represented in the model.

3.3. Application to estimate impact on household resources

3.3.1. Crop yields and farm income

As illustrated in Fig. 9, the impact of different treatments of inorganic and organic fertilisers was highly variable, with yields of crops treated with inorganic fertiliser out-performing organic fertiliser treatments in the first decade, but improving with continued inputs of organic fertiliser, so that productivity for the three treatments (100% inorganic fertiliser, 50:50 inorganic and organic fertiliser, and 100% organic fertiliser) was more similar by the last decade of the simulation (Fig. 10). Over the whole period of the simulation, if dung was not used as a fuel, the net income from the 100% inorganic fertiliser and the integrated fertiliser management (50:50 inorganic fertiliser and organic fertiliser) was not significantly different, as indicated by the overlap of the error bars in the simulated values (Fig. 11). This is the case, even if dung would otherwise have been used as a fuel. However, the 100% organic fertiliser treatment resulted in a significant loss of income of 482 (± 339) US\$ y^{-1} compared to using 100% inorganic fertiliser, which increases to 691 (± 339) US\$ y^{-1} if dung would otherwise have been used as a fuel. Therefore, this analysis suggests that, short term income is benefitted by applying inorganic fertiliser, or 50:50 inorganic and organic fertiliser rather than applying 100% organic fertiliser. However, this analysis has as yet taken no account of the longer term impacts of improved soil structure on crop yields, and does not consider the benefits to yield provided by other macro- and micro-nutrients contained in the organic fertiliser.

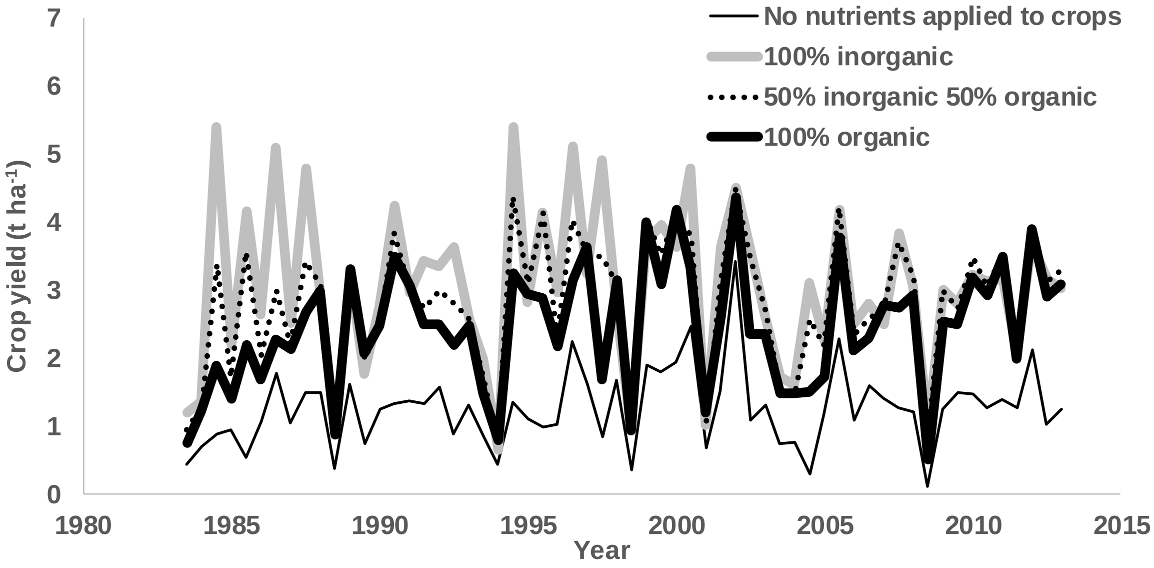


Fig. 9. Crop yields predicted for different treatments at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, using recorded weather data from 1983 to 2013.

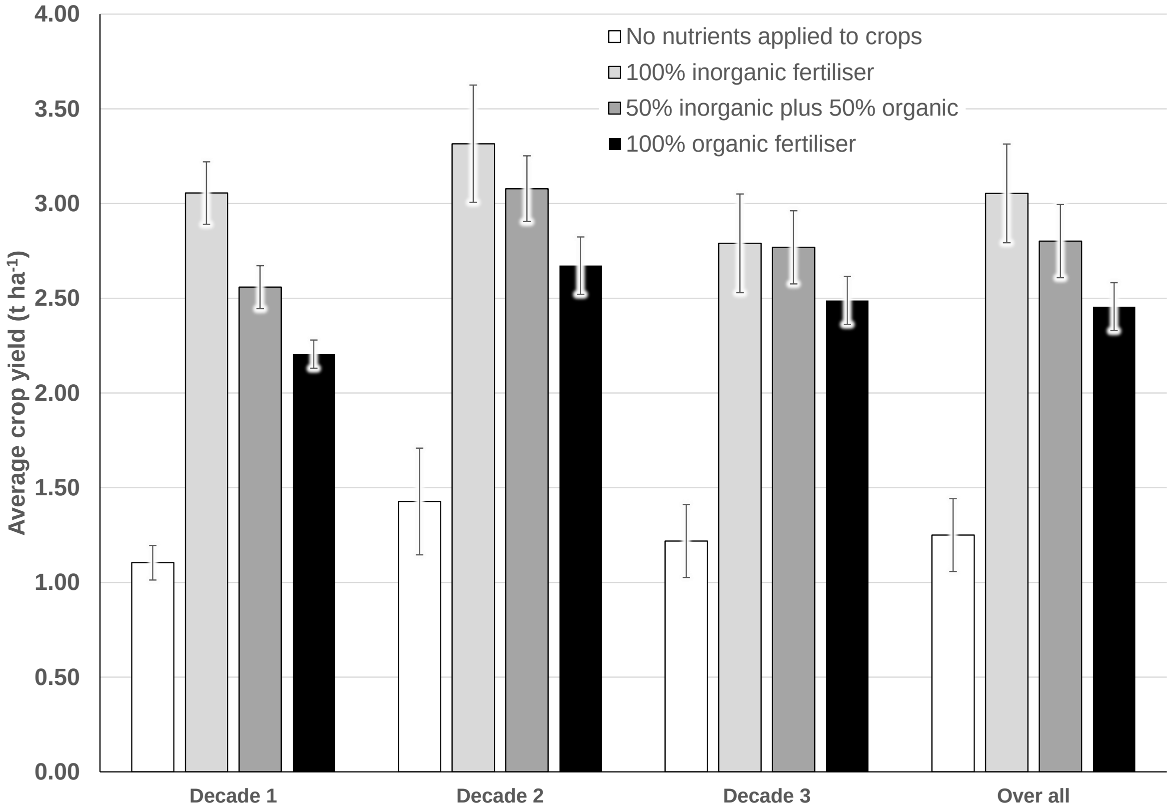


Fig. 10. Decadal average crop yields predicted for different treatments at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, using recorded weather data from 1983 to 2013. Note: error bars represent the standard error in the simulated crop yields in that time period.

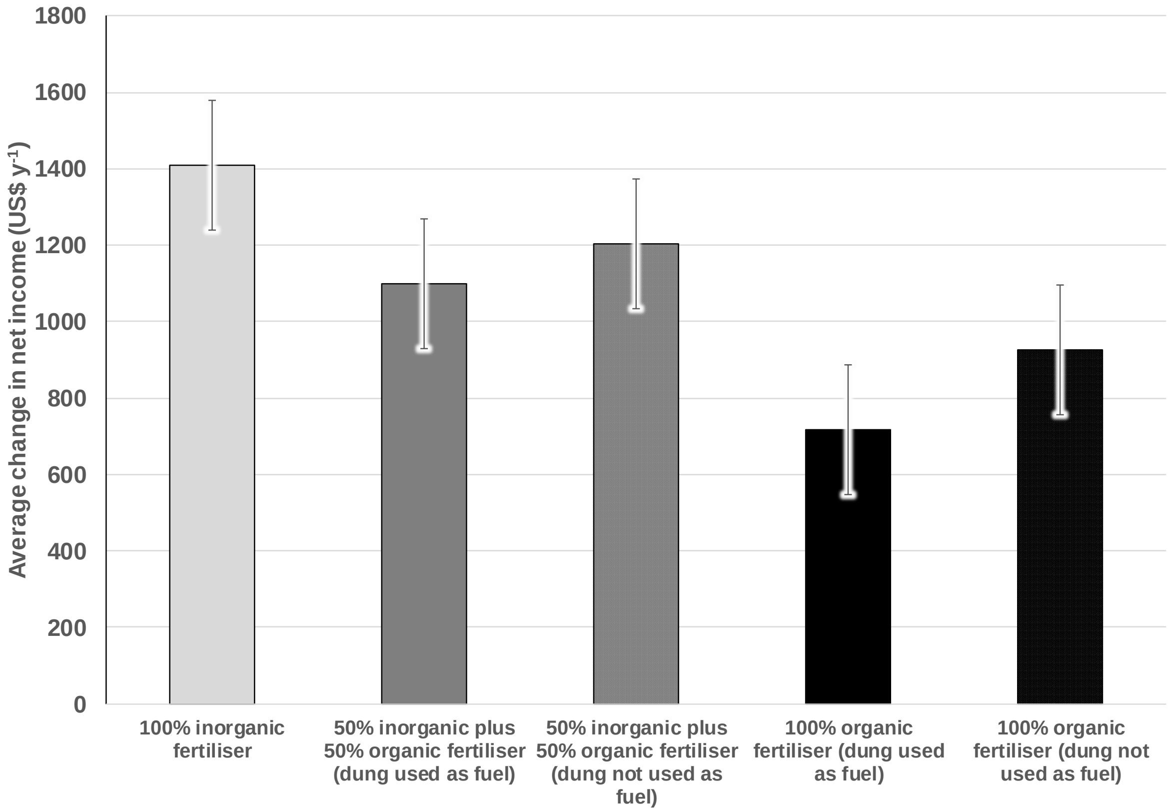


Fig. 11. Average change in net income over 30 years of treatment compared to the control where no nutrients are applied to crops as predicted for different treatments at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, using recorded weather data from 1983 to 2013. Note: the error bar shows the average error calculated using the bias estimated for simulation of crop yield. Black bars show results for households where dung would otherwise be used as a fuel, and net income accounts for the cost of replacing the dung diverted to organic fertiliser with an alternative fuel (assumed to be liquefied petroleum gas). Grey bars show results for households where dung is not used as a fuel

3.3.2. Soil carbon

The longer term potential benefits due to improvements in soil structure can be seen in the C sequestered over the course of the simulation; linear equations fitted over the first 30 years suggested that average C sequestration was -0.01 t ha^{-1} y^{-1} (i.e. net loss in soil C) when no additional nutrients were applied, 0.11 t ha^{-1} y^{-1} for the 100% inorganic fertiliser treatment, 0.22 t ha^{-1} y^{-1} for 50% inorganic and 50% organic fertiliser, and 0.25 t ha^{-1} y^{-1} for 100% organic fertiliser. Over the longer term, the rate of C sequestration declined until the soil reached steady state with respect to the new inputs (Fig. 12); when no additional nutrients were added, the steady state showed a decline in soil C by -3.8 (±0.4) t ha^{-1} to a C content of 8 (±0.8) t ha^{-1} (steady state soil C of 0.45 (±0.04)%), whereas for 100% inorganic fertiliser, the soil C at steady state increased by 8 (±0.7) t ha^{-1} to 20 (±2) t ha^{-1} (steady state soil C of 1.1 (±0.1)%), for 50% inorganic and 50% organic fertiliser by 11 (±1) t ha^{-1} to 23 (±2) t ha^{-1} (steady state soil C of 1.3 (±0.1)%), and for 100% organic fertiliser by 14 (±1) t ha^{-1} to 26 (±2) t ha^{-1} (steady state soil C of 1.4 (±0.1)%). This suggests that there are significant long term benefits to SOC of applying N, and this is significantly higher if N is applied as organic fertiliser, either all as organic fertiliser, or as part of an integrated fertiliser management system (for example 50:50 inorganic and organic fertiliser), which would benefit both SOC and crop yield.

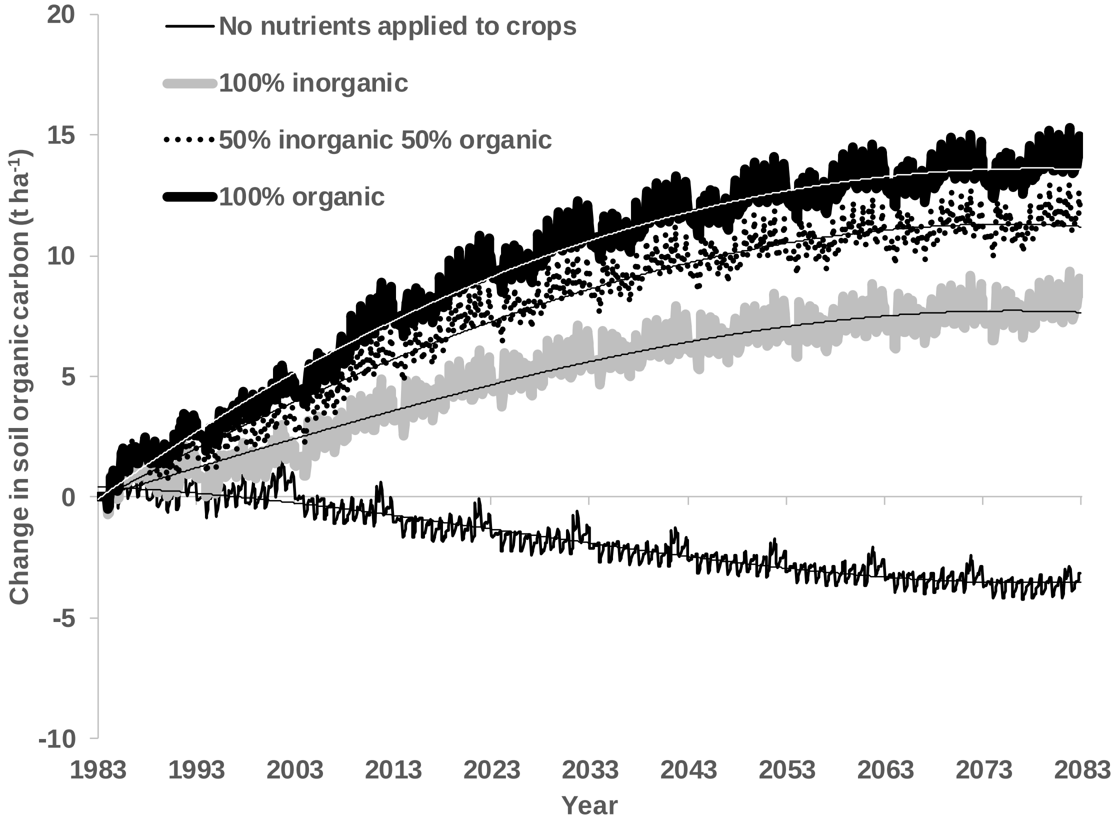


Fig. 12. Carbon sequestration predicted for different treatments at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, using recorded weather data from 1983 to 2013. Note: Thin lines show the 3rd order parabolic trendlines fitted to change in soil organic carbon with respect to carbon at the start of the simulation.

3.3.3. Soil water

The change in soil organic matter had a strong impact on the amount of water held in the soil (Fig. 13). The annual average water content increased 3.6% compared to the control after 100 years when 100% inorganic fertiliser was applied, 4.8% when 50% inorganic and 50% organic fertiliser was applied, and 5.5% when 100% organic fertiliser was applied. Therefore, applying more N as organic fertiliser is likely to have a significant positive impact on resilience of crops to droughts.

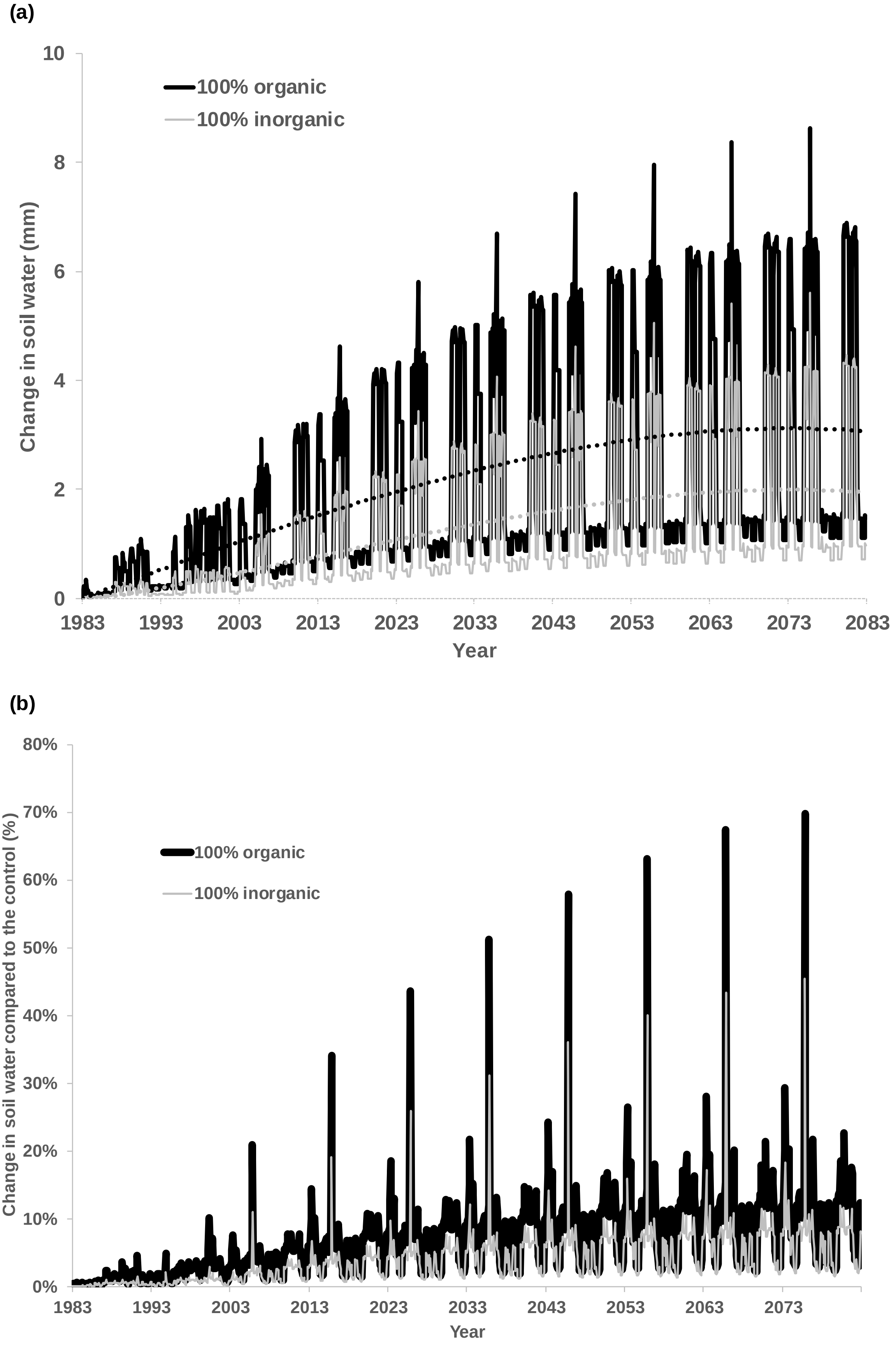
(a)
10
8
6
4
2
0
Change in soil water (mm)
100% organic
100% inorganic
1983
1993
2003
2013
2023
2033
2043
2053
2063
2073
2083
Year
(b)
80%
70%
60%
50%
40%
30%
20%
10%
0%
Change in soil water compared to the control (%)
100% organic
100% inorganic
1983
1993
2003
2013
2023
2033
2043
2053
2063
2073
Year

Fig. 13. Change in soil water in the top 15cm soil following inorganic and organic fertiliser treatments compared to the control where no nutrients were applied (a) in water content (mm), and (b) as a percentage of the water content of the control. Predicted values at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, using recorded weather data from 1983 to 2013, and assuming future weather as given for 2003 to 2013. Note: dotted lines indicate the 3rd order polynomial trendline fitted to the dataset of the same colour.

3.3.4. Soil nitrogen and nitrogen use efficiency

The change in soil organic matter increases the soil N supply as shown in Fig. 13. This results in an increase in the efficiency of inorganic fertiliser N use, defined here as the yield over the total amount of inorganic fertiliser N applied, from 3.4 (±0.2) % for 100% inorganic fertiliser application to 6.7 (±0.4) % for 50% inorganic and 50% organic fertiliser application. Therefore, applying organic fertiliser not only increases the whole farm efficiency of N use by recycling organic N back to the soil, but also increases the efficiency with which the inorganic N is used.

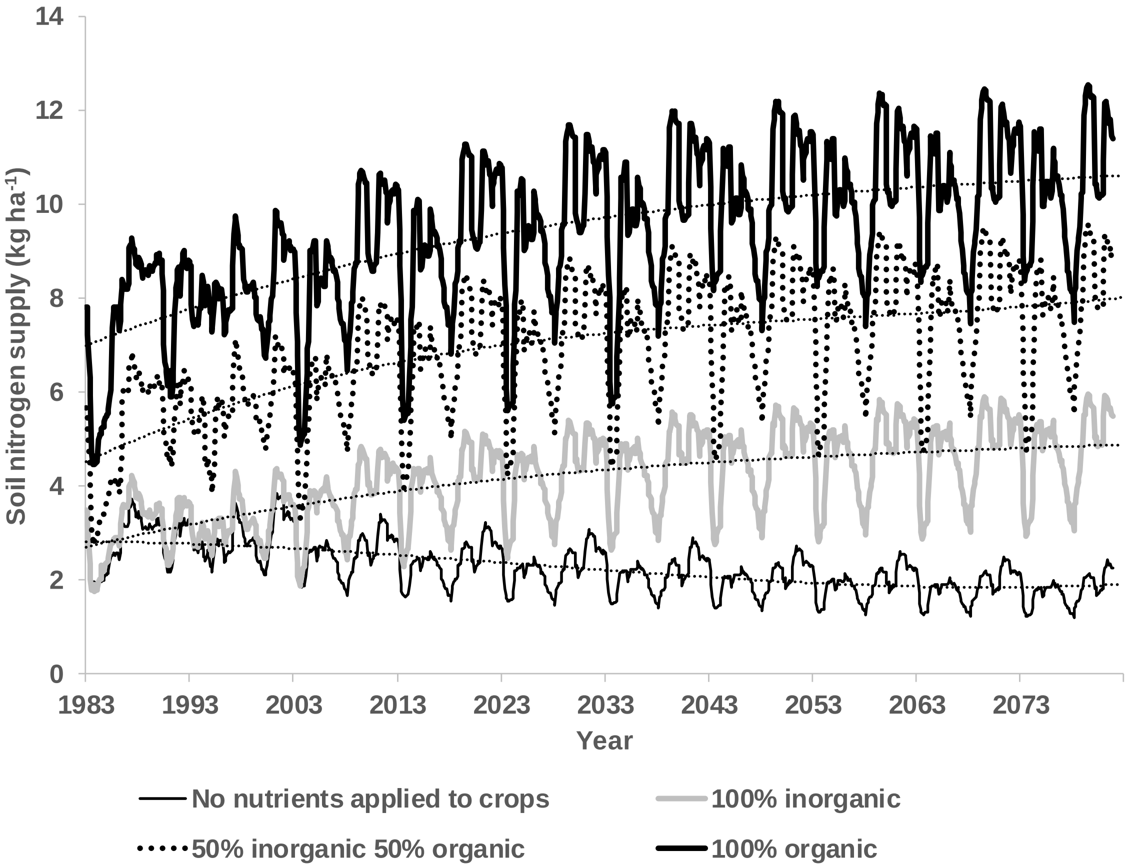


Fig. 14. Soil nitrogen supply (12 month average) in the top 15cm of soil at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, using recorded weather data from 1983 to 2013, and assuming future weather as given for 2003 to 2013. Note: dotted lines indicate the fitted 3rd order polynomial trendlines; soil nitrogen supply expressed as the moving 12 month average to allow visual distinction of graphs.

3.3.5. How can we reduce degradation of soils in India?

Soils of India are degrading. In the state of Haryana, Singh (2000) reported declining levels of soil organic matter with increasing use of chemical inputs. Using the Century model, Milne et al. (2007) and Bhattacharyya et al. (2007) predicted that the SOC stocks in the Indo-Gangetic planes will further decline between the years 1990 and 2030. Loss of SOC has been highlighted as a key indicator of soil degradation (Karlen and Rice, 2015) as it has a significant impact on the biomass yield of the crops grown (Lenka et al., 2017). Therefore, to maintain the long-term productivity of Indian soils, use of organic fertilisers should be encouraged. This has been reflected in the spread of conservation agriculture or “Climate Smart Agriculture” in North West India (Punjab and Haryana) where crop residues are retained to reduce burning, so also increasing SOC (Jat et al., 2019a, b). The example application at Parbhani, Maharashtra, India, demonstrates that in the longer term, applying all of the recommended rate of N as organic fertiliser sequesters a significant amount of C, improving the productivity of the soil. However, this resulted in a significant short-term economic cost to the household due to a reduction in yield. This is because only a portion of the N contained in the fertiliser is in a form that can be immediately taken up by the crop.

To achieve widespread uptake of recommendations to reduce soil degradation by using more organic fertiliser, it is important that short-term farm incomes do not suffer. However, these simulations suggest there is a trade-off in ecosystem services provided by inorganic and organic fertilisers, with inorganic fertilisers providing the best yields, while organic fertilisers provide the greatest increase in soil organic matter. To achieve comparable yields, either the quantity of organic fertiliser applied should be increased, or the quality of the organic fertiliser should be improved so that it delivers more N to the crop. Using the same quality of organic fertiliser as applied in these field trials, the ORATOR simulations suggest that the application rate would need to be increased by 75% to achieve the same yield as seen in the treatment with 100% inorganic fertiliser.

However, if the dung would otherwise be used as a household fuel, net farm income in the short term could be further reduced by applying more organic fertiliser due to the need to replace fuel with LPG. This could result in poorer farmers, who are likely to own a lower number of livestock and to use the dung available to them as a fuel, becoming trapped in a downward spiral of declining soil productivity due to low organic inputs, resulting in falling yields and long term degradation of their annual incomes.

Methods that could be used to increase the quality of the compost applied include anaerobic digestion (Smith et al., 2014) or improved composting techniques, such as vermicomposting, which uses worms to increase the rate of decomposition, and NADEP composting, which uses layered plant wastes, cow manure and soil to increase the volume of compost produced and conserve moisture during the dry season (Basak et al., 2013). Using organic manure as a feedstock for a biogas digester provides both fuel and organic fertiliser, so could have double benefits. However, this has an initial start-up cost that may be prohibitive for the poorer farmer. A cheaper option would be to use improved pyrolysis cookstoves to reduce the demand for dung as a fuel, while also providing biochar which can be used as a soil improver (Smith et al., 2015). However, the pyrolysis process burns off many of the nutrients in the organic waste, so the biochar would need to be enriched with an available source of N to be used as an effective fertiliser. Further analysis is needed to determine the potential to use these alternatives and to interpret the impact on farm income and the wider environment.

Another possible mechanism to achieve short term income benefits when using dung for soil improvement is to adjust the balance between the price of fertiliser and the price of LPG. In India, the price of fertiliser is controlled by the Nutrient Based Subsidy, which in 2014-15 was 20.875 INR kg^{-1} (0.30 US$ kg^{-1} assuming exchange rate of 0.1446 INR per US$, Currency Converter, 2019) (Government of India, Department of Fertilizers, 2019). The price of LPG is also controlled by subsidy, currently between 29.6 and 32.8 INR kg^{-1} (0.43 to 0.47 US$ kg^{-1}), depending on location (Good Returns, 2019b). If all subsidies were removed, the change in income for the 100% organic compared to the 100% inorganic fertiliser treatment would be further reduced from -380 US$ y^{-1} with subsidies to -417 US$ y^{-1} without them. If subsidies on fertilisers were removed while subsidies on LPG were increased by 150% of the current rate (as high as is possible without paying people to use LPG), there is still a net cost of using organic compared to inorganic fertilisers (**¡Error! No se encuentra el origen de la referencia.**). Therefore, it appears from these simulations that policy makers have limited scope to use subsidy levels to encourage soil improvement.

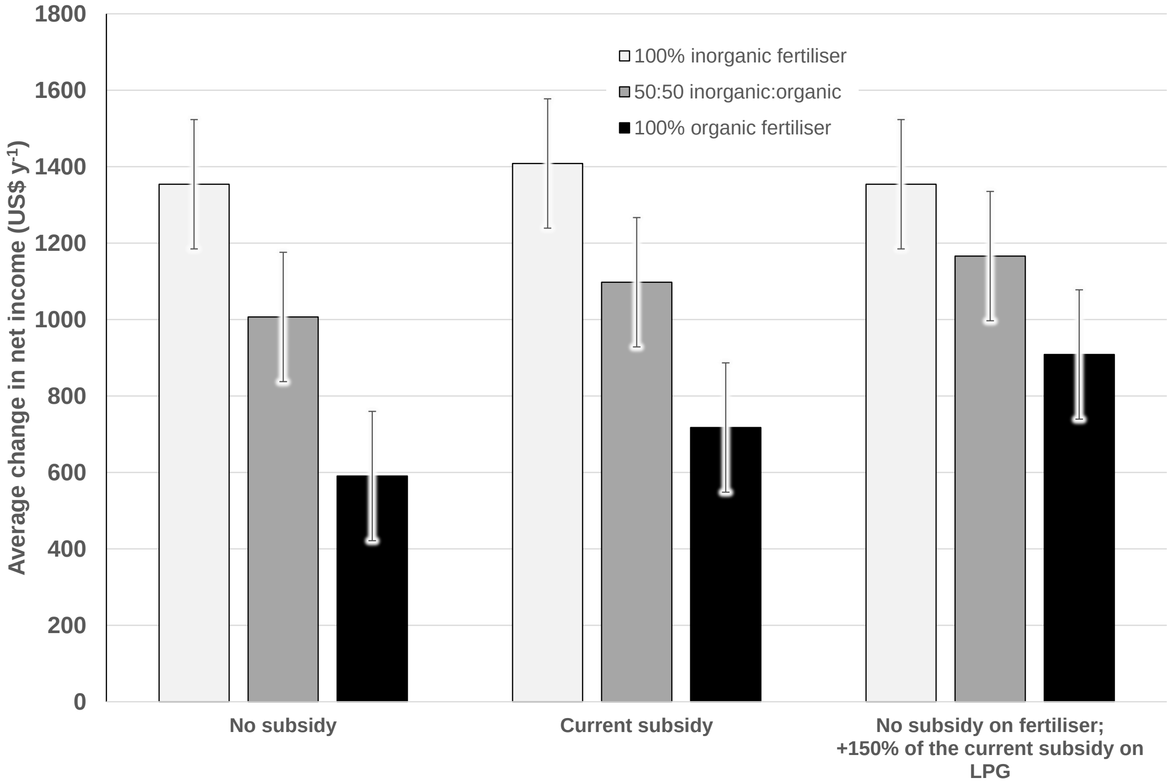


Fig. 15. Average change in net income in the first 10 years of treatment compared to the control where no nutrients are applied to crops. Predictions for different treatments with different subsidy levels assuming dung would otherwise be used as a household fuel and is replaced by LPG. Simulations at Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, using recorded weather data from 1983 to 1993. Note: the error bar shows the average error calculated using the bias estimated for simulation of crop yield.

Integrated fertiliser management, represented here by the treatment where the recommended rate of N was applied 50% as inorganic and 50% as organic fertiliser, did not significantly reduce net household income, even if the dung would have otherwise been used as a fuel (Fig. 11). Furthermore, at steady state, this treatment sequestered 83% as much C as was sequestered by applying all N as organic fertiliser. Therefore, this compromise is a good option to both maintain short-term net income while also providing long-term improvements to the productivity of the soil. Many other authors have highlighted integrated fertiliser management as a good option for improving long term productivity (e.g. Meena et al., 2019; Singh et al., 2019; Yadav et al., 2019), and Nath et al. (2018) specifically identified integrated fertiliser management using NPK fertiliser and farmyard manure as being one of the management practices with most potential for C sequestration in small-holder farms in India. The work presented here corroborates the recommendation to use integrated fertility management to improve soils while maintaining farm income from crop production.

4. Conclusions

In this paper we have described a new systems model, developed specifically to look at how uses of organic resources impact soil processes, food production, water and energy use and farm income in low and middle income countries. We have presented its partial evaluation against data from a long term experiment in India and quantified the uncertainty associated with the simulations of yield and SOC in this environment. We then used the defined uncertainty in the model to demonstrate its application to assess the impact on households of different applications of inorganic and organic fertilisers to crops.

This model provides an advance in bringing together simple but comprehensive simulations of the wider farming system, allowing the impact of different management choices on the overall availability of different resources in different parts of the farm to be assessed. It differs from many economic-centric models in that the description of the changes occurring in the soils are process-based, allowing feedbacks and interactions to be better understood. This is important because it allows us to understand the full impacts of decisions made by farmers and to assess some of the factors that may encourage better long term management of soils.

The application of the ORATOR model presented illustrates the importance of considering the wider farming system when making recommendations for improved management, especially in a low to middle income context, where a change based on partial evidence could have a catastrophic impact on the potential of the household to achieve food, energy and water security. Further work is needed to evaluate the impact and acceptability of such recommendations with farmers. Future work should also further develop the model to include description of the impact of different management practices on household well-being, and analysis of the impact of different uses of organic wastes on indoor air quality and exposure to pathogens. This will provide a more complete picture of the overall impacts of different decisions on sustainable farm production, household income, and human well-being and health.

Acknowledgements

We are grateful for support from the DFID-NERC El Niño programme in project NE P004830, “Building Resilience in Ethiopia’s Awassa region to Drought (BREAD)”, the ESRC NEXUS programme in project IEAS/POO2501/1, “Improving organic resource use in rural Ethiopia (IPORE)”, and the NERC ESPA programme in project NEK0104251 “Alternative carbon investments in ecosystems for poverty alleviation (ALTER)”. We are also grateful to Dr. V.U.M. Rao (Former Project Coordinator, AICRP on Agrometeorology, CRIDA, Hyderabad) and Dr. S.K. Chaudhari (DDG, NRM Division, KAB-II, ICAR, New Delhi) for their assistance in collecting meteorological data of Parbhani, Maharashtra.

References

Adimassu, Z., Alemu, G., Tamene, L., 2019. Effects of tillage and crop residue management on runoff, soil loss and crop yield in the Humid Highlands of Ethiopia. Agr. Syst. 168, 11-18.

Bakhshianlamouki, E., Masia, S., Karimi, P., van der Zaag, P., Sušnik, J., 2020. A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia lake Basin, Iran. Sci. Tot. Environ. 708, 134874. doi: 10.1016/j.scitotenv.2019.134874 PMID: 31796284

Bhattacharyya, T., Pal, D.K., Easter, M., Batjes, N.H., Milne, E., Gajbhiye, K.S., Chandran, P., Ray, S.K., Mandal, C., Paustian, K., Williams, S., Killian. K., Coleman, K., Falloon, P., Powlson, D.S., 2007. Modelled soil organic carbon stocks and changes in the Indo-Gangetic Plains, India from 1980 to 2030. Agric. Ecosyst. Environ. 122, 84 – 94.

Basak, B.B., Biswas, D.R., Pal, S., 2013. Soil biochemical properties and grain quality as affected by organic manures and mineral fertilizers in soil under maize-wheat rotation. Agrochimica LVII – N, 49-66.

Bell, M.J., Jones, E., Smith, J., Smith, P., Yeluripati, J., Augustin, J., Juszczak, R., Olejnik, J., Sommer, M., 2012. Simulation of soil nitrogen, nitrous oxide emissions and mitigation scenarios at 3 European cropland sites using the ECOSSE model. Nutr. Cycl. Agroecosys. 92, 161-181.

Benbi, D.K., Singh, R., Singh, G., Sandhu, K.S., Singh, R., Saggar, S., 1993. Response of dryland wheat to fertilizer nitrogen in relation to stored water, rainfall and residual farm yard manure. Fert. Res. 36, 63-70.

Bolinder, M.A., Janzen, H.H., Gregorich, E.G., Angers, D.A., Van den Bygaart, A.J., 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agr. Ecosyst. Environ. 118, 29–42

Bradbury, N.J., Whitmore, A.P., Hart, P.B.S., Jenkinson, D.S., 1993. Modelling the fate of nitrogen in crop and soil in the years following application of ^{15}N-labelled fertilizer to winter wheat. J. Agr. Sci. – Camb. 121, 363-379.

Celestina, C., Hunt, J.R., Sale, P.W.G., Franks, A.E., 2019. Attribution of crop yield responses to application of organic amendments: A critical review. Soil Till. Res. 186, 135-145.

Chen, Y., Camps-Arbestain, M., Shen, Q., Singh, B., Luz Cayuela, M., 2018. The long-term role of organic amendments in building soil nutrient fertility: a meta-analysis and review. Nutr. Cycl. Agroecosys. 111, 103–125. https://doi.org/10.1007/s10705-017-9903-5.

Coleman, K., Jenkinson, D.S., 1996. RothC-26.3. A model for the turnover of carbon in soil. In: Powlson DS, Smith P, Smith JU, editors. Evaluation of soil organic matter models using existing long-term datasets. NATO ASI Series I, Vol 38. Springer, Berlin, pp. 237–246.

Currency converter, 2019. https://www.xe.com/currencyconverter/ accessed March 2019

Datta, A., Mandal, B., Badole, S., Chaitany, K.A., Majumder, S.P., Padhan, D., Basak, N., Barman, A., Kundu, R., Narkhede, W.N., 2018. Interrelationship of biomass yield, carbon input, aggregation, carbon pools and its sequestration in Vertisols under long-term sorghum-wheat cropping system in semi-arid tropics. Soil Till. Res. 184, 164-175.

De Barros, I., Pacheco, E.P., De Carvalho, L., Wilson, H., 2017. Integrated emergy and economic performance assessments of maize production in semiarid tropics: comparing tillage systems. J. Environ. Account. Man., 5, 211-232.

Government of India, Department of Fertilizers, 2019. Fertilizer Policy. http://fert.nic.in/page/fertilizer-policy (accessed May 2019).

Falloon, P., Smith, P., Coleman, K., Marshall, S., 1998. Estimating the size of the inert organic matter pool for use in the Rothamsted carbon model. Soil Biol. Biochem. 30, 1207–1211.

Food and Agriculture Organisation of the United Nations (FAO), 2015. Status of the world soils report. Intergovernmental Technical Panel on Soils - Food and Agriculture Organisation of the United Nations, Rome pp. 607 http://www.fao.org/3/a-i5199e.pdf

Farmer’s Portal. https://farmer.gov.in/MarketWiseDailyReport.aspx (accessed April 2019).

Gedefaw, M., Denghua, Y., Hao, W., Alemu, B., Chanie, M., Agitew, G., 2018. Evaluation of adoption behavior of soil and water conservation practices in the Simein Mountain National Park, Highlands of Ethiopia. Cogent Food Agric. 4, 1513782.

Good Returns, 2019a. https://www.goodreturns.in/lpg-price-in-maharashtra-s20.html (accessed April 2019).

Good Returns, 2019b. https://www.goodreturns.in/lpg-price.html (accessed May 2019)

Grundmann, G.L., Rolston, D.E., 1987. A water function approximation to degree of anaerobiosis associated with denitrification. Soil Sci. 144, 437-441.

Guerra, A.J.T., Fullen, M.A., do Carmo Oliveira Jorge M., Bezerra, J.F.R., Shokr, M.S., 2017. Slope processes, mass movement and soil erosion: a review. Pedosphere, 27, 27-41. https://doi.org/10.1016/s1002-0160(17)60294-7.

Haregeweyn, N., Tsunekawa, A., Nyssen, J., Poesen, J., Tsubo, M., Tsegaye Meshesha, D., Schütt, B., Adgo, E., Tegegne, F., 2015. Soil erosion and conservation in Ethiopia: A review. Prog. Phys. Geog. 39, 750-774. doi: 10.1177/0309133315598725

Henault, C., Germon, J.C., 2000. NEMIS, a predictive model of denitrification on the field scale. Eur. J. Soil Sci. 51, 257-270.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D., Obersteiner, M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. P. Natl. Acad. Sci. 110, 20888–20893. doi:10.1073/pnas.1308149110.

Holzworth, D.P., Snow, V., Janssen, S., Athanasiadis, I.N., Donatelli, M., Hoogenboom, G., White, J.W., Thorburn, P., 2015. Agricultural production systems modelling and software: Current status and future prospects. Env. Mod. & Soft. 72, 276 – 286.

Hundal, S.S., De Datta, S.K., 1984. Water table and tillage effects on root distribution, soil water extraction, and yield of sorghum grown after wetland rice in a tropical soil. Field Crop. Res. 9, 291-303.

ICAR, 2019. All India co-ordinated research project on integrated farming systems. Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani-431402, Maharashtra, India Annual reports. http://www.iifsr.res.in/AICRP/annual.html (accessed June 2019).

Iiyama, M., Mukuralinda, A., Ndayambaje, J.D., Musana, B.S., Ndoli, A., Mowo, J.G., Garrity, D., Ling, S., Ruganzu, V., 2018. Addressing the paradox – the divergence between smallholders' preference and actual adoption of agricultural innovations. International Journal of Agricultural Sustainability. 16, 472–485.

Jat, H.S., Datta, A., Choudhary, M., Yadav, A.K., Choudhary, V., Sharma, P.C., Gathala, M.K., Jat, M.L., McDonald, A., 2019a. Effects of tillage, crop establishment and diversification on soil organic carbon, aggregation, aggregate associated carbon and productivity in cereal systems of semi-arid Northwest India. Soil Tillage Res. 190, 128-138.

Jat, H.S., Datta, A., Choudhary, M., Sharma, P.C., Yadav, A.K., Choudhary, V., Gathala, M.K., Jat, M.L., McDonald, A., 2019b. Climate Smart Agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of North-West India. Catena. 181, 104059.

Karlen, D.L., Rice, C.W., 2015. Soil Degradation: Will Humankind Ever Learn? Sustainability 7, 12490-12501.

Kirk, J.T.O., 2011. Light and Photosynthesis in Aquatic Ecosystems. Third edition. Cambridge University Press, Cambridge.

Kirkegaard, J.A., Lilley, J.M., 2007. Root penetration rate – a benchmark to identify soil and plant limitations to rooting depth in wheat. Aust. J. Exp. Agric. 47, 590-602.

Kushwah, S.K., Dotaniya, M.L., Upadhyay, A.K., Rajendiran, S., Coumar, M.V., Kundu, S., et al., 2014. Assessing carbon and nitrogen partition in kharif crops for their carbon sequestration potential. Natl. Acad. Sci. Lett. 37, 213–217.

Leith H., 1972. Modelling the primary productivity of the world. Nature and Resources, UNESCO VIII 2:5-10.

Lenka, N.K., Jaiswal, S.P., Thakur, J.K., Lenka, S., Mandal, A., Dwivedi, A.K., Lakaria, B.L., Biswas, A.K., Shukla, A.K., Yashona, D.S., 2017. Soil degradation effect on soil productivity, carbon pools and soil enzyme activity. Curr. Sci 112, 2434-2439.

Li, X.-Y., 2000. Soil and water conservation in arid and semiarid areas: the Chinese experience. Ann. Arid Zone 39, 1-18.

Loveland, P., Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil Till. Res. 70, 1–18. https://doi.org/10. 1016/S0167-1987(02)00139-3.

Matthews, R.B., Rivington, M., Muhammed, S., Newton, A.C., Hallett, P.D., 2013. Adapting crops and cropping systems to future climates to ensure food security: The role of crop modelling. Global Food Security 2, 24-28.

Meena, B.P., Biswasa, A.K., Singh, M., Chaudhary, R.S., Singh, A.B., Das, H., Patra, A.K., 2019. Long-term sustaining crop productivity and soil health in maize–chickpea system through integrated nutrient management practices in Vertisols of central India. Field Crop Res. 232, 62–76.

Milne, E., Paustian, K., Easter, M., Sessay, M., Al-Adamat, R., Batjes, N.H., Bernoux, M., Bhattacharyya, T., Cerri, C.C., Cerri, C.E.P., Coleman, K., Falloon, P., Feller, C., Gicheru, P., Kamoni, P., Killian, K., Pal, D.K., Powlson, D.S., Williams, S., Rawajfih, Z., 2007. An increased understanding of soil organic carbon stocks and changes in non-temperate areas: National and global implications. Agr. Ecosys. Environ. 122, 125–136.

Mohanty, M., 2015. Simulation of nitrogen release from organic materials in the soybean/wheat cropping systems on Vertisols in central India. PhD thesis submitted to the University of Queensland.

Murphy, B.W., 2015. Impact of soil organic matter on soil properties–a review with emphasis on Australian soils. Soil Res. 53, 605–635. https://doi.org/10.1071/SR14246.

Nath, A.J., Lal, R., Sileshi, G.W., Das, A.K., 2018. Managing India's small landholder farms for food security and achieving the “4 per Thousand” target. Sci. Tot. Environ. 634, 1024–1033.

Parton, W.J., Mosier, A.R., Ojima, D.S., Valentine, D.W., Schimel, D.S., Weier, K., Kulmala, A.E., 1996. Generalized model for N_2 and N_2O production from nitrification and denitrification. Global Biogeochem. Cy. 10, 401-412.

Prosdocimi, M., Tarolli, P., Cerdà, A., 2016. Mulching practices for reducing soil water erosion: A review. Earth-Sci. Rev. 161, 191-203, https://doi.org/10.1016/j.earscirev.2016.08.006.

Reid, J.B., 2002. Yield response to nutrient supply across a wide range of conditions 1. Model derivation. Field Crop Res. 77, 161–171.

Ren, F., Zhang, X., Liu, J., Sun, N., Sun, Z., Wu, L., Xu, M., 2018. A synthetic analysis of livestock manure substitution effects on organic carbon changes in China's arable topsoil. Catena, 171, 1-10. https://doi.org/10.1016/j.catena.2018.06.036.

Ruis, S.J., Blanco-Canqui, H. 2017. Cover Crops Could Offset Crop Residue Removal Effects on Soil Carbon and Other Properties: A Review. Agron. J. 109, 1785-1805.

Scopel, E., Triomphe, B., Affholder, F., Macena Da Silva, F.A., Corbeels, M., Humberto Valadares Xavier, J., Lahmar, R., Recous, S., Bernoux, M., Blanchart, E., de Carvalho Mendes, I., De Tourdonnet, S., 2013. Conservation agriculture cropping systems in temperate and tropical conditions, performances and impacts. A review. Agron. Sustain. Dev. 33, 113-130. https://doi.org/10.1007/s13593-012-0106-9.

Setia, R., Smith, P., Marschner, P., Gottschalk, P., Baldock, J., Verma, V., Smith, J.U., 2012. Simulation of salinity effects on soil carbon: past, present and future carbon stocks. Environ. Sci. Technol. 46, 1624-1631.

Shrestha, B.M., Chang, S.X., Bork, E.W., Carlyle, C.N., 2018. Enrichment planting and soil amendments enhance carbon sequestration and reduce greenhouse gas emissions in agroforestry systems: a review. Forests 9, 369. https://doi.org/10.3390/f9060369.

Singh, D.K., Pandey, P.C., Nanda, G., Gupta, S., 2019. Long-term effects of inorganic fertilizer and farmyard manure application on productivity, sustainability and profitability of rice-wheat system in Mollisols. Arch. Agron. Soil Sci. 65,

Singh, P., Gundimeda, H., Stucki, M., 2014. Environmental footprint of cooking fuels: a life cycle assessment of ten fuel sources used in Indian households. Int. J. Life Cycle Ass. 19, 1036-1048.

Singh, R.B., 2000. Environmental consequences of agricultural development: a case study from the Green Revolution state of Haryana, India. Agr. Ecosys. Environ. 82, 97–103.

Smith, J.U., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M.D.A., Reginster, I., Ewert, F., 2005. Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. Glob. Change Biol. 11, 2141–2152.

Smith, J.U., Smith, P., 2007. Environmental Modelling. An Introduction. Oxford University Press, Oxford. 180pp.

Smith, J., Coleman, K., Gottschalk, P., Bellarby, J., Richards, M., Nayak, D., et al., 2010. Estimating changes in national soil carbon stocks using ECOSSE – a new model that includes upland organic soils. Part I. Model description and uncertainty in national scale simulations of Scotland. Climate Res. 45, 179-192.

Smith, J., Abegaz, A., Matthews, R., Subedi, M., Orskov, E.R., Tumwesige, V., et al., 2014. What is the potential for biogas digesters to improve soil carbon sequestration in Sub-Saharan Africa? Comparison with other uses of organic residues, Biomass Bioenerg. 70, 73-86.

Smith, J.U., Fischer, A., Hallett, P.D., Homans, H.Y., Smith, P., Abdul-Salam, Y., Emmerling, H.H., Phimister, E.C., 2015. Sustainable use of organic resources for bioenergy, food and water provision in rural Sub-Saharan Africa. Renew. Sust. Energ. Rev. 50, 903-917.

Smith, P., Smith, J.U., Powlson, D.S., McGill, W.B., Arah, J.R.M., Chertov, O.G., et al. 1997. A comparison of the performance of nine soil organic matter models using seven long-term experimental datasets, in Smith P., Powlson D.S., Smith J.U., Elliott E.T., editors. Evaluation and comparison of soil organic matter models using datasets from seven long-term experiments. Geoderma 81, 153-225.

Smith, P., House, J.I., Bustamante, M., Sobock, J.A., Harper, R., Pan, G., West, P.C., Clark, J.M., Adhya, T., Rumpel, C., Paustian, K., Kuikman, P., Cotrufo, M.F., Elliott, J.A., Mcdowell, R., Griffiths, R.I., Asakawa, S., Bondeau, A., Jain, A.K., Meersmans, J., Pugh, T.A.M., 2016. Global change pressures on soils from land use and management. Global Change Biol. 22, 1008–1028. doi: 10.1111/gcb.13068.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55–94.

TNAU. Agritech portal; Nutrient management, price of fertilizers (2013) http://agritech.tnau.ac.in/agriculture/agri_nutrientmgt_priceoffertilizers.html (accessed April 2019).

Tóth, B., Weynants, M., Nemes, A., Makó, A., Bilas, G., Tóth, G., 2015. New generation of hydraulic pedotransfer functions for Europe: New hydraulic pedotransfer functions for Europe. Eur. J. Soil Sci. 66, 226–238.

Uchino, H., Watanabe, T., Ramu, K., Sahrawat, K.L., 2013. Effects of nitrogen application on sweet sorghum (*Sorghum bicolor (L.) Moench*) in the semi-arid tropical zone of India. Jpn. Agr. Res. Q. 47, 65-73.

UN Convention to Combat Desertification (UNCCD), 2016. Achieving land degradation neutrality at the country level. Building blocks for LDN target. Global Mechanisms of the UNCCD. https://knowledge.unccd.int/sites/default/files/inline-files/Building%20blocks%20for%20LDN%20target%20setting_0.pdf

UNCCD, 2019. Land degradation neutrality. https://knowledge.unccd.int/topics/land-degradation-neutrality.

UN Statistics Division Energy Statistics Database (United Nations, 2013); http://data.un.org/Explorer.aspx (accessed April 2019).

Unkovich, M., Baldock, J., Forbes, M., 2010. Chapter 5 - Variability in harvest index of grain crops and potential significance for carbon accounting: examples from Australian agriculture. In: Advances in Agronomy. Advances in Agronomy Vol. 105. Academic Press pp. 173-219.

van Ittersum, M.K., Ewert, F., Heckelei, T., Wery, J., Olsson, J.A., Andersen, E., Bezlepkina, I., Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A.E., van der Wal, T., Wien, J.E., Wolf, J., 2008. Integrated assessment of agricultural systems – A component-based framework for the European Union (SEAMLESS). Agric. Sys. 96, 150–165.

Wolka, K., Mulder, J., Biazin, B., 2018. Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: A review. Agr. Water Manage. 207, 67-79.

Yadav, S.P., Singh, S.C., Yadav, S., Yadav, S.K., Tiwari, A.K., Sharma, B.L., 2019. Integrated nutrient management approaches for enhancing production potential and sustainability of sugarcane (saccharum spp. hybrid) plant–ratoon system in North Region of India. Sugar Tech. 21, 170–175. https://doi.org/10.1007/s12355-018-0641-z.

Zaks, D.P.M., Ramankutty, N., Barford, C.C., Foley, J.A., 2007. From Miami to Madison: Investigating the relationship between climate and terrestrial net primary production. Global Biogeochem. Cy. 21, GB3004. doi:10.1029/2006GB002705.

Zavattaro, L., Bechini, L., Grignani, C., van Evert, F.K., Mallast, J., Spiegel, H., Sandén, T., Pecio, A., Vicente Giráldez Cerverag, J., Guzmáng, G., Vanderlinden, K., D'Hose, T., Ruysschaert, G., ten Berge, H.F.M., 2017. Agronomic effects of bovine manure: A review of long-term European field experiments. Eur. J. Agron. 90, 127-138.