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Evaluating the Century C model using long-term fertilizer trials in the Indo-Gangetic Plains, India

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Abstract

The GEFSOC Project developed a system for estimating soil carbon (C) stocks and changes at the national and sub-national scale. As part of the development of the system, the Century ecosystem model was evaluated for its ability to simulate soil organic C (SOC) changes in environmental conditions in the Indo-Gangetic Plains, India (IGP). Two long-term fertilizer trials (LTFT), with all necessary parameters needed to run Century, were used for this purpose: a jute (*Corchorus capsularis* L.), rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) trial at Barrackpore, West Bengal, and a rice–wheat trial at Ludhiana, Punjab. The trials represent two contrasting climates of the IGP, *viz.* semi-arid, dry with mean annual rainfall (MAR) of <800 mm and humid with >1600 mm. Both trials involved several different treatments with different organic and inorganic fertilizer inputs. In general, the model tended to overestimate treatment effects by approximately 15%. At the semi-arid site, modelled data simulated actual data reasonably well for all treatments, with the control and chemical N + farm yard manure showing the best agreement (RMSE = 7). At the humid site, Century performed less well. This could have been due to a range of factors including site history. During the study, Century was calibrated to simulate crop yields for the two sites considered using data from across the Indian IGP. However, further adjustments may improve model performance at these sites and others in the IGP. The availability of more long-term experimental data sets (especially those involving flooded lowland rice and triple cropping systems from the IGP) for testing and validation is critical to the application of the model's predictive capabilities for this area of the Indian sub-continent.

Keywords: Soil organic carbon; Century; Crop yield; India

1. Introduction

The Global Environment Facility Soil Organic Carbon (GEFSOC) Project (Milne et al., 2007) (project number GFL-2740-02-4381) developed the GEFSOC modelling system, a generically applicable system for estimating SOC stocks and changes at the national and sub national scale. The system was developed using data from 4 contrasting eco regions: the Brazilian Amazon, Jordan, Kenya and the Indian part of the Indo-Gangetic Plains (IGP). These regions were chosen for their contrasting climates and soil types and the fact that they provide examples of those areas underrepresented by current soil C models. The system can be used to make spatially explicit SOC stock and stock change estimates using two soil C models (RothC and Century) and the empirical IPCC method. Layers of soils, climate, historical and current land use, and land management data, collated in a consistent format, are linked to the two models and the IPCC method, *via* GIS. The system itself

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comprises of the Graphical User Interface (GUI) and a number of components that run the three methods (Easter et al., 2007).

One of the stages in the development of the GEFSOC System was evaluation of the performance of the component models (RothC and Century) when applied to datasets from the case study areas and when used to model crops grown in these areas (Milne et al., 2007). The use of long-term datasets to evaluate the performance of soil organic matter (SOM) models has been well documented (Addiscott et al., 1995; Smith et al., 1996, 1997). The future predictive capacity of a model obviously cannot be tested against future datasets, however, the models' ability to simulate past experimental datasets spanning several years or decades may give an indication of the models' capacity to predict change under varying environmental conditions (Smith et al., 1997). Measured and modelled data can be compared both qualitatively (by visual comparison of graphed modelled and measured data) and quantitatively by a number of statistical tests. The large number of specific input parameters that many SOM models require means that, more often than not, modelled data is 'tuned' using measured data before a comparison is made. This makes standard tests such as the Students t test inappropriate as they assume complete independence between datasets. Smith et al. (1996) outline a range of statistical methods that are suitable for the quantitative evaluation of soil organic matter models. These include statistics that quantify the association and coincidence between simulated and measured data sets. These statistics have been put together in a computer program called 'MODEVAL' (Smith et al., 1996).

In order to evaluate the performance of the Century model, long-term data sets are needed that include information on soil C, soil texture, bulk density, crop yields and management practices. Many long-term experiments have been carried out in the Indian IGP (Bhattacharyya et al., 2005a), however most of these lack data on some of the parameters needed to run the Century model or are unavailable. Out of the available long-term datasets in the Indian IGP (Abrol et al., 2000; Bhattacharyya et al., 2005a), only two sites had adequate data for all of the parameters needed for model evaluation. Titled according to their order of listing in Singh et al. (2004a), these sites are Trial 4 (Barrackpore, 24 Parganas North in West Bengal) and Trials 14/15 (Fatehpur, Ludhiana in Punjab) from the All India Coordinated Research Project. These two sites also happened to be located in contrasting climatic areas, with Trial 4, Barrackpore, being in a humid area and Trials 14/15, Ludhiana, being in a semi-arid area (Bhattacharyya et al., 2004) (Fig. 1). This study therefore used data from the trials at these two sites to evaluate the performance of the Century Ecosystem model in contrasting environmental conditions found in the Indian part of the Indo-Gangetic Plains (IGP).

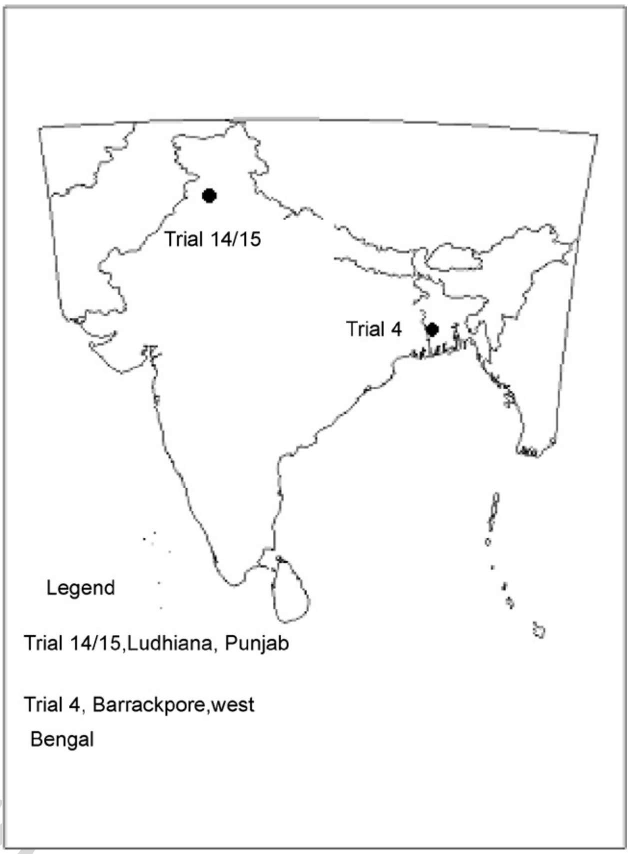

Fig. 1. Location of two long-term fertilizer trials in the Indian Indo-Gangetic Plains.

2. Materials and methods

2.1. The Century ecosystem model

The Century ecosystem model is described by Parton et al. (1987). In brief, it is a general ecosystem model that simulates the dynamics of C, N, P and S in different plant/soil systems through an annual cycle over centuries to millennia. Century has plant productivity, water movement and nitrogen leaching sub-models that determine the turnover of nutrients within the system. Century allows the simulation of complex agricultural management systems including crop rotations, tillage practices, fertilization, irrigation, grazing and harvest methods. Century was originally developed for grasslands (Parton et al., 1987) but has since been extended to agricultural crops, forests, Savanna systems (Paustian et al., 1992; Carter et al., 1993; Parton, 1996; Gijsman et al., 1996) and temperate and tropical forest systems (Romanya et al., 2000; Kirschbaum and Paul, 2002; Cerri et al., 2004). It uses a monthly time step utilising monthly average maximum and minimum temperatures and monthly precipitation data (Parton et al., 1987; Parton and Rasmussen, 1994; Parton, 1996). The grassland/crop and forest systems have different plant production sub-models that are linked to a common soil organic matter (SOM) and nutrient cycling sub-model

(Parton et al., 1994). It comprises two forms of litter, *viz. metabolic* and *structural* and three SOM compartments, *viz. active*, *slow* and *passive*, which differ in their potential rates of SOM decomposition. C leaving the *active* organic matter component is either released as CO_2 or goes into the 'slow' organic C pool with the split determined by soil texture. Soil texture also regulates the rate of transfer between *slow* and *passive* forms.

2.2. Long-term fertilizer trial (LTFT) details

The study used existing available data from two LTFT sites in the Indian IGP. All information used had to be gathered from publications, as this was the only source of information available. In Singh et al. (2004a), the two trials are named 'Trial 4' (Barrackpore, 24 Parganas North in West Bengal) and 'Trials 14/15' (Fatehpur, Ludhiana in the Punjab). In this paper, we use the same names (Trial 4 and Trial 14/15) to allow the reader to easily cross reference information with prior publications. Selected biophysical and management details for both the chosen sites are presented in Table 1.

Trial 4 was carried out at Barrackpore, West Bengal, over a 30-year period (1972–2001) (Manna et al., 2006; Bhattacharyya et al., 2005a; Reddy et al., 2003; Saha et al., 2000). Climate in Barrackpore is humid (MAR > 1600 mm). Average maximum and minimum temperatures during the experimental period were 31 and 21 °C, respectively (Saha et al., 2000). Information on land use prior to the start of the experiment was taken from Manna et al. (2006) who describe the site as uncultivated and covered by 'natural forest vegetation such as perennial weeds and grasses' prior to 1968. In 1969 rice was grown, followed by jute in 1970 (Manna et al., 2006). In Century, this was modelled as a 7000-year equilibrium forest system followed by a heavily grazed grass/weed system (to represent a much degraded forest system with little regeneration) from the early 1800s to the beginning of cultivation in 1968. The year 1968 was depicted as one of clearing and preparation involving heavy tillage events. During the experimental period, three crops were grown in rotation, jute, rice and wheat. The trial involved eight different management strategies consisting of different combinations of chemical fertilizer and farm yard manure (FYM). Chemical fertilizer application rates were based on percentages of the recommended doses for rice, wheat and jute. The recommended dose (100%) for rice and wheat was 120 kg ha^{-1} N and for jute 60 kg ha^{-1} N. Five of these management strategies were chosen for model evaluation (Table 2) on the basis that they were most representative of current practices found in India. Bulk density (BD) was not routinely measured in most of the LTFT trials carried out in the Indian IGP. In the case of Barrackpore, only one BD measurement could be found in the literature in Saha et al. (2000). Data on changes in bulk density throughout the experimental period were not available, therefore bulk density had to be assumed to be constant for all times and treatments and was taken as 1.3 Mg m^{-3} (Saha et al., 2000).

Further details of Trial 4 can be found in Reddy et al. (2003) and Saha et al. (2000). Composite soil C data, amalgamated from all treatments in 1971 was reported for 0–22.5 cm depth in Saha et al. (2000). Soil C values for 1975–1995 were estimated from a graph presented in the same publication. Soil C values for 2001 were presented for depths 0–15 and 15–30 cm (Manna et al., 2006; Reddy et al., 2003). In lieu of reported information, values for 2001 were

Table 1
Selected biophysical and management details for two long-term fertilizer trials in the Indian IGP (trial names are taken from Singh et al., 2004a)

Site characteristics	Trial 4	Trial 14/15
Location	Barrackpore, West Bengal, India	Ludhiana, Punjab, India
Latitude/longitude	22°45′N, 88°26′E	30°56′N, 75°52′E
Altitude (m)	9	247
Annual rainfall (mm)	1698	800
Soil	Sandy loam	Loamy sand
Clay (%)	18.0	12.6
Silt (%)	28.0	8.9
Sand (%)	54.0	78.5
Bulk density (g m^{-3})	1.3 (reported in Saha et al., 2000)	1.65 (assumption made by Singh et al., 2004a,b)
pH	7.1	7.6
Initial total organic C (%)	0.71 (0–22.5 cm depth)	0.36 (0–15 cm depth)
Experiment start year	1971	1988
Site history	Uncultivated perennial weeds and grasses prior to 1968; first crop sown in 1969	Maize–wheat rotation for about 20 years
Soil group	Typic Eutrudepts[a], Eutri-Gleic Cambisols[b], Eutric Cambisols[c]	Typic Ustipsamments[a], Haplic Arenosols[b], Haplic Arenosols[c]
Soil series	Nilgangj (Eutrudepts)	Fatehpur (Ustipsamments)

N.B.: Source for Trial 4: Manna et al. (2006), Reddy et al. (2003) and Saha et al. (2000). Source for Trial 14/15: Singh et al. (2000, 2004a,b).
[a] USDA Soil Taxonomy (Soil Survey Staff, 2003).
[b] IUSS Working Group WRB (2006).
[c] FAO-UNESCO (FAO, 1988).

Table 2
Experimental descriptions of the two trials used for model validation in the Indian IGP

Region	Crop rotation	Trial number	N application kg ha^{-1} jute–rice–wheat
West Bengal, Barrackpore	Jute–rice–wheat	4-1	Control
West Bengal, Barrackpore	Jute–rice–wheat	4-2	30–60–60
West Bengal, Barrackpore	Jute–rice–wheat	4-4	90–180–180
West Bengal, Barrackpore	Jute–rice–wheat	4-5	60–120–120, +FYM
West Bengal, Barrackpore	Jute–rice–wheat	4-8	60–120–120
Punjab, Ludhiana	Rice–wheat	14/15-1	Control
Punjab, Ludhiana	Rice–wheat	14/15-2	150N
Punjab, Ludhiana	Rice–wheat	14/15-3	52N, +GM
Punjab, Ludhiana	Rice–wheat	14/15-4	150N, +WS
Punjab, Ludhiana	Rice–wheat	14/15-5	52N, +GM, +WS
Punjab, Ludhiana	Rice–wheat	14/15-6	62N, +FYM
Punjab, Ludhiana	Rice–wheat	14/15-7	FYM, +GM

N.B.: N: nitrogen/fertilizer amounts for jute, rice and wheat, respectively, for Trial 4; FYM: 5.8 Mg ha^{-1} dry matter addition from farm yard manure; GM: green manure; WS: wheat straw. *Source*: Reddy et al. (2003), Saha et al. (2000) and Singh et al. (2000, 2004b).

estimated for 0–22.5 cm depth by adding one-half of the reported value for 15–30 cm to the value reported for 0–15 cm. All soil C estimates were then adjusted by multiplying by 0.89 (the ratio of 20:22.5) to enable comparison with output from the Century model, which simulates a depth of 20 cm. Mean monthly weather data (precipitation, monthly mean maximum and minimum temperature) were used for the pre-experimental periods and actual regional weather was used for the experimental years.

Trials 14 and 15, as reported in Singh et al. (2004a), represent the rice and wheat crops, respectively, of the same experimental rotation. The experiment began in 1988 at the farm of the Punjab Agricultural University, Ludhiana (Punjab, India) with a rice–wheat cropping rotation (Singh et al., 2004b). Soil at the site is a Fatehpur loamy sand (Typic Ustipsamment). Climate in the area is semi-arid with mean annual rainfall (MAR) <800 mm. During October to June evaporation exceeds precipitation. Mean monthly maximum air temperature at the site ranges from 19 °C in January to 38 °C in June and minimum between 5 °C in January and 26 °C in July (Rekhi et al., 2000). The site was modelled as a maize–wheat rotation for 20 years prior to the beginning of the experiment (Singh et al., 2004b). This experiment included different management strategies involving different combinations of chemical fertilizer (based on % applications of the recommended dose), FYM, green manure (GM) and wheat straw (WS). Further details are given in Singh et al. (2000, 2004b). Seven management strategies were chosen from these trials, again on the basis that they were representative of current practices in the Indian IGP (Table 2). The assumption made by Singh et al. (2004b) that bulk density was 1.65 g m^{-3} was also used for modelling purposes and (lacking other data) was assumed constant across years and treatments. Measured soil C data were reported for depth 0–15 cm. Reported soil C data were adjusted for comparison to the Century simulated depth of 20 cm by assuming a declining soil C value with depth and multiplying reported values by 1.17. That is, the SOC at the depth 15–20 cm was assumed to have an amount approximately equal to 1/6 of the value found in the 0–15 cm sample. These assumptions were based on data presented in Reddy et al. (2003) and Manna et al. (2006), where 1/3 of the mean of reported values for SOC found at depth 15–30 cm is equal to 1/6 of the mean of reported values in 0–15 cm. Mean weather data (Singh et al., 2004a) (the only data available) was used for the pre-experimental and the experimental periods.

2.3. *Parameterisation of the Century model using regional crop yield data*

The ability of the Century model to predict changes in SOC turnover depends largely on the plant productivity sub-models, which determine plant production and returns to the soil. Century already has sub-models for rice, wheat and jute (the three crops used in Trials 4 and 14/15). However, these crop files have associated management practices (sowing/planting time, irrigation, addition of fertilizer and FYM, yield and method of harvesting) that are very different from those used in the IGP. Due to climatic constraints and traditions, management practices and varieties of wheat and rice crops vary greatly between the northern part of the IGP (Punjab, Haryana and western Uttar Pradesh), the central part of the IGP (central and eastern Uttar Pradesh and part of Bihar) and the eastern part of the IGP (eastern Bihar, West Bengal and part of Tripura). In order to address this, we gathered data on crop and crop management information for rice, wheat and jute crops across the Indian IGP (this was done as part of a larger exercise that gathered information on a total of 42 crops for the same area (Bhattacharyya et al., 2005b)). This information was then used to create rice and wheat files in Century that are specific to the Indian IGP. For example, four options were created for wheat in the IGP and three for rice (Table 3). These crop files, specific to the Indian IGP, were then used in the model evaluation process.

Table 3
Regional rice and wheat crop modules, specific to the Indian Indo-Gangetic Plains added to the Century model

	Wheat			
Abbreviation	IGPWR	IGPWN	IGPWC	IGPWE
Description	Wheat rainfed	Irrigated wheat, northern IGP	Irrigated Wheat central IGP	Irrigated wheat, northern IGP
Sowing time	Mid October–Early November	Mid November	Late November–Early December	3rd week December
Duration (months)	4–5	4–5	4–5	4–5
Irrigation	No irrigation	4–6	4–6	4–6

	Rice		
Abbreviation	IGPRP	IGPRM	IGPRS
Description	Rice pre-monsoon	Rice monsoon	Rice boro (summer)
Sowing time	April–May	June–July	December–January
Duration (months)	4	5	4
Irrigation	–	–	Weekly (12–15 Nos.)

2.4. Model evaluation using the two trial sites

The Century model was run to simulate changes in soil C contents in the 0–20 cm depth (of soils) at the two chosen LTFT sites in the IGP, India. The output from the model was then compared with available field data to evaluate model performance. This was done both qualitatively (by visual examination of graphed out put) and quantitatively using the MODEVAL computer program, which carries out a range of statistical tests designed to appraise the performance of SOC models when compared to measured datasets (Smith et al., 1996). Quantitative analysis was carried out for measured *versus* modelled data for the periods 1988–1999 for Trial 14/15 and 1976–2001 for Trial 4.

Due to a lack of reported data, it was necessary to estimate some earlier soil C data from published graphs (Trial 4). It was also necessary to adjust values to estimate soil C to the 0–20 cm depth simulated in the Century model. The literature on the two trials reports that they used the wet oxidation method of Walkley and Black (1934) or the dichromate oxidation method of Nelson and Sommers (1975) to determine soil C. Differences in soil C measurements resulting from the use of different chemical methods or chemicals as opposed to dry combustion methods are difficult to determine, being highly dependent on soil type (Landon, 1991). Therefore, no adjustments have been applied to reported or estimated values to account for differences that may result from using these analytical methods.

3. Results

3.1. Measured and modelled SOC

Results of the Century modelling for SOC are shown in Figs. 2–4. Figs. 2a–c and 3a and b show the trajectory of SOC through time for the two trials that were modelled. Tables 4 and 5 show a statistical comparison of measured SOC over time compared with modelled SOC over the same time period for each treatment in the two trials. Selected statistics reported are: the sample correlation coefficient (r), the coefficient of determination (CD) (which effectively measures the proportion of the total variance in the observed data that is explained by the predicted data), the root mean square error (RMSE) which is a measure of coincidence between measured and modelled values and M, the mean difference between observations and simulations which gives an indication of bias (or consistent error) (Smith et al., 1996).

Fig. 4a–c shows the modelled and reported differences in ‘treatment effects’ for both trials (‘treatment effects’ refers to the differences between observed SOC for each treatment mean and the control within each experiment).

For Trials 14/15, which were carried out in a semi-arid climate, measured data for all treatments (except the control) showed an increase in soil C from 1988 to 1999 (Fig. 2a–c). In all cases, the modelled output followed the trend of the actual data reasonably well; this is illustrated by correlation coefficients for all treatments (except the control) being greater than zero (Table 4). This shows a positive correlation between measured and modelled data. In the case of the control, measured data increase slightly and then level out, whereas the model predicts a slight decline over time (Fig. 2b). This leads to a small negative correlation between measured and modelled data ($r = -0.7$, Table 4). Despite this, the RMSE for the control was the lowest of any treatment (7.09) indicating that the differences between measured and modelled data were small. The lower the RMSE, the more accurate the simulation (Smith et al., 1996).

For Trials 14/15, RMSE was less than 12 for all treatments, showing that the model was simulating actual datasets relatively well in all cases. T6, the 62N + FYM treatment had the lowest RMSE, after the control and had a slightly lower M value, indicating bias (or consistent error) was less for this treatment (Table 4). T3, T4 and T5 also all had low RMSE and M values. All of these treatments involved a combination of chemical N fertilizer and organic amendments (farmyard manure, green manure or wheat straw). RMSE values were higher for T7 (organic amendments only) and T2 (high chemical fertilizer only),

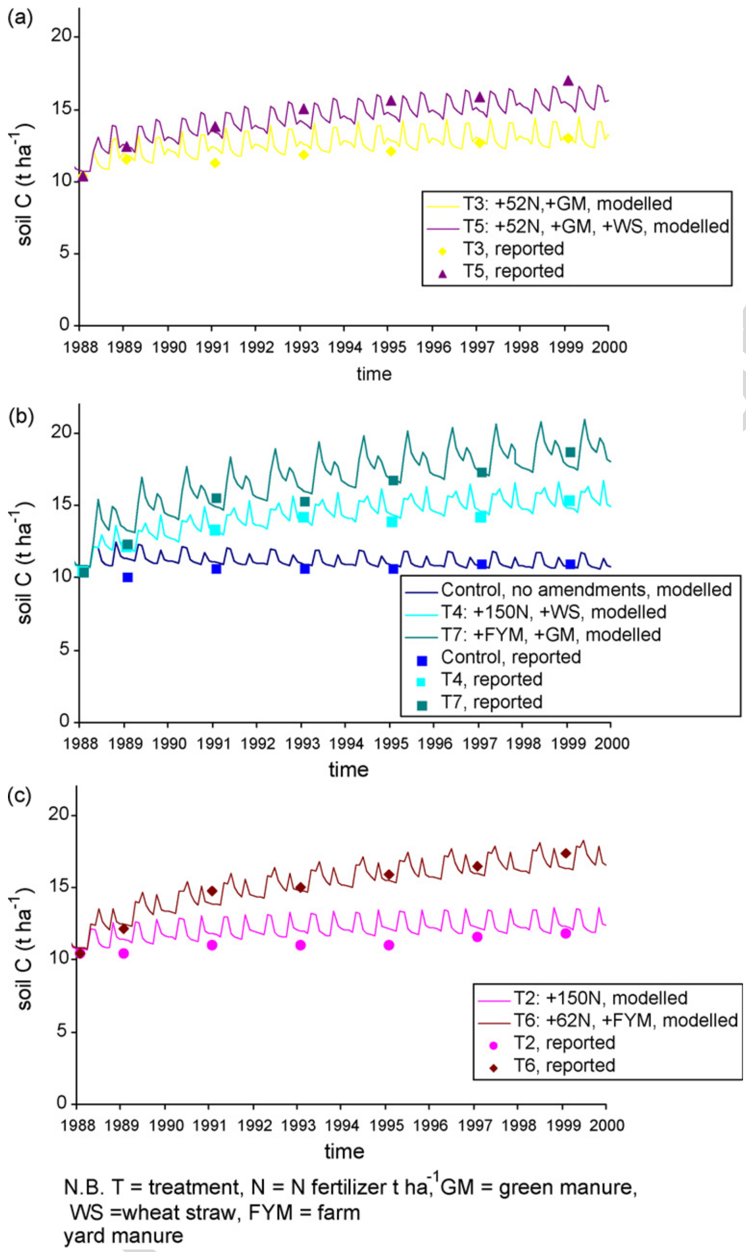

Fig. 2. (a–c) Modelled and measured soil carbon over time for seven management regimes included in the long-term fertilizer trials (Nos. 14 and 15) at Ludhiana, Punjab, India.

suggesting that Century works best for the conditions in Ludhiana, when a combination of chemical N fertilizer and organic inputs are modelled.

Trial 4 (Barrackpore) was carried out in the humid area and involved a triple cropping rotation (jute–rice–wheat) (Table 1). Statistical analysis was carried out for three of the treatments (Control, T5 and T8) where enough data were available. Overall, Century modelled this trial less well than Trial 14/15, with small negative correlations between measured and modelled data for all three treatments analysed (Table 5). RMSE was lowest for the control (19.07). Treatment T5 (chemical N fertilizer + FYM) had an RMSE of almost 36, and a relatively high *M* value (Table 5). This indicates that bias or consistent error is affecting the way Century is modelling this particular treatment. Fig. 3a shows the poor fit between modelled and measured data for treatment T5 in Trial 4.

However, in Trial 4, when all treatments are considered, Century modelled results for soil C agreed well with 2001 field measurements from Manna et al. (2006) and Reddy et al. (2003) in terms of both C stocks and treatment differences for four of the five experiments (Fig. 3a and b). In comparison with the earlier data derived from graphs in Saha et al. (2000), Century did not predict as sharp a decline in C stocks between the initial cultivation and 1976. As a result, Century stocks are higher than reported stocks

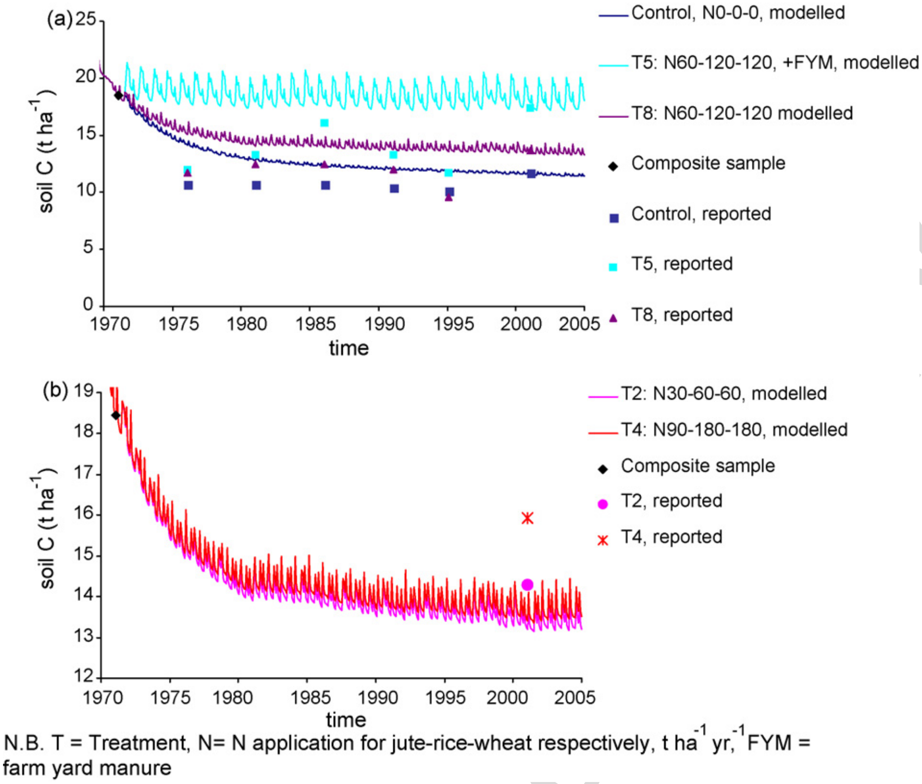

Fig. 3. (a and b) Modelled and measured soil carbon over time for five management regimes included in the long-term fertilizer trial (No. 4) at Barrackpore, West Bengal.

between 1976 and 1995. Saha et al. (2000) reported an initial decade long increase in C stocks from 1976 to 1986 for the experiments presented here, followed by a decade of declines in soil C stocks from 1986 to 1995. This period of decline is difficult to explain with the available management and climate information and in the light of the later values reported by Manna et al. (2006) and Reddy et al. (2003). Century does not model a similar decline. Century results did not mirror the increase in soil C indicated in the 2001 field data for experiment T4 (90–180–180 N ha^{-1} $year^{-1}$ jute–rice–wheat, respectively) (Fig. 3b). Century may not be fully simulating an increase in residue biomass production, above ground and below ground, stimulated by this excess fertilizer application.

Overall, the Century model appears to predict soil C stocks and treatment effects (for fertilizer and manure additions) relatively well, but better in the semi-arid site than in the humid site, based upon the comparisons in Figs. 2–4. When all available field data are considered together for these two trials, in general, the model tended to overestimate treatment effects by approximately 15% (Fig. 4a and b). This overestimation occurs largely in the earlier values from Trial 4. If only the most recent data available (2001 measurements for Trial 4 and 1999 measurements for Trial 14/15) are considered, the fit of Century simulated treatment effects on soil C to the reported treatment effects is very good (Fig. 4c).

3.2. *Measured and modelled yield*

The Century model was parameterised using regional crop data from across the whole of the Indian IGP (Section 2). Fig. 5 shows reported yield for the 3 crops grown in the two trials (rice, jute and wheat) *versus* modelled yield. A reasonably good association can be seen with an R^2 value of 0.71.

4. Discussion

The evaluation of the Century model using the Ludhiana and the Barrackpore long-term fertilizer trials gives an indication of the performance of the Century model when simulating different environmental conditions found in the Indian IGP. As pointed out in Section 2, these were the only two trials for which SOC and the other necessary parameters for evaluating Century were available. Abrol et al. (2000) published a volume of results from the All India Coordinated Fertilizer Trials in 2000, however these studies (with the exception of Ludhiana and Barrackpore) do not report SOC. The Ludhiana trial is based on a very sandy region of the IGP. Soils in this region are coarse textured and drain freely. Conditions at the Barrackpore trial are humid and more typical of those found in the larger area of the Indian IGP.

Century appeared to model changes in SOC more successfully at the semi-arid site (Ludhiana) than at the

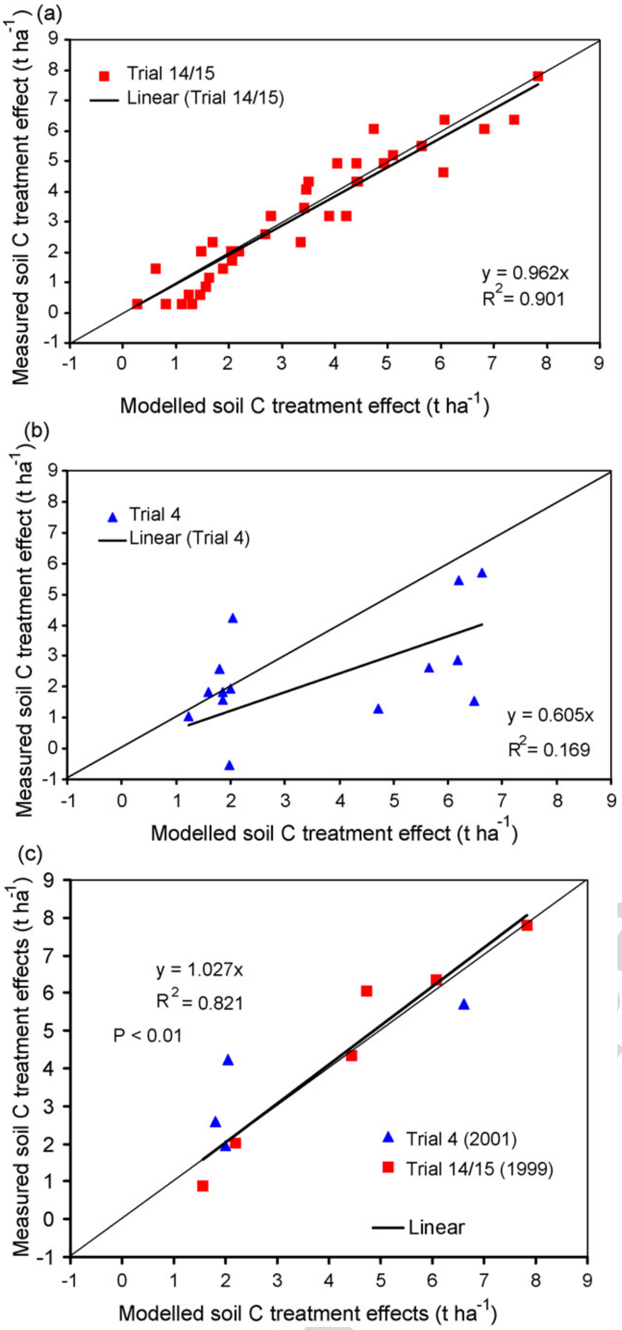

Fig. 4. (a) Differences in treatment effects (modelled *vs.* reported) for Trial 14/15. Correlation coefficient for the comparison is 0.95. (b) Differences in treatment effects (modelled *vs.* reported) for Trial 4. Correlation coefficient for the comparison is 0.51. (c) Differences in treatment effects (modelled *vs.* reported) for Trials 4 and 14/15 for the latest available year of data.

humid site (Barrackpore). SOC levels were low to start with at Ludhiana and inputs were comparatively high, perhaps making the increasing trend in SOC easy to capture. It might be reasonable to expect a higher degree of spatial heterogeneity in soil C in a site recently converted to cropland as opposed to one cropped continuously over decades. This post-conversion noise might be contributing to the early results at Barrackpore. It would appear, from the available data, that in the heavier soils at the humid Barrackpore site (Table 1), SOC levels increased before decreasing then increasing again for all treatments. A similar pattern for all treatments suggests that analytical differences between years could be influencing the dataset. Unfortunately archived samples were not available for reanalysis. Saha et al. (2000) reported an over all decline in SOC when describing this data set. However, given the fluctuating increases and decreases between sampling times, this is a difficult conclusion to draw. Century predicted little change over time for SOC for the 50N and 50N + FYM treatments. It did, however, predict a decline for the control treatment, which was consistent with the dataset and the description by Saha et al. (2000).

For all treatments at Barrackpore, Century overestimated SOC stocks prior to 2001. This overestimation could have been due to uncertainties in the history of land use prior to the start of the experiment and the subsequent effects on soil properties. Historical details on native vegetation and land management after cultivation are difficult to obtain. Generic or ‘‘best guess’’ histories prior to the start of an experiment may lead to an overestimation or underestimation of initial soil C stocks during the experimental period. This offset in initial C stocks influences the entire simulation of the experiment.

Overestimation by Century of the Barrackpore trial may also have been due to the fact that this trial involved a triple cropping rather than a double cropping system. Triple cropping systems are common in humid areas of tropical countries. It may be that further development of the Century model is needed to improve performance when modelling returns to the soil and decomposition under triple cropping systems. Similarly the drainage conditions at Barrackpore (a heavy soil, compared to the coarse textured freely draining soil in Trial 14/15) may also have been more difficult for Century to simulate. This is particularly pertinent, given the fact that lowland rice was grown at both sites and that this paper is one of the few examples of Century being used to model SOC under flooded lowland rice. Further investigation of the performance of Century when modelling SOC turnover in flooded crops such as lowland rice is needed.

Modelled *versus* reported average crop yields for three major crops of the IGP are shown in Fig. 5. Yield averages are for 1988–2000 for Trial 14/15 and for 1971–1995 for Trial 4. Rice and wheat production values were available for both the trials and jute production values were available for just one site. In general, Century appeared to simulate production reasonably well for all three crops. Reported rice yields from the two sites span a large range as do Century rice yields. Treatment effects on rice yields are well simulated. The reported and simulated yield ranges for wheat and jute are smaller. When all three crops were considered together, the correlation coefficient was 0.84. Regression statistics indicate that for all the crops in these experiments, production is slightly overestimated by 4%. This is actually a desired result, as there are crop losses in the

Table 4
Quantitative statistical analysis of modelled (Century) *vs.* reported soil organic carbon data for Trial 14/15 in the Indian IGP

Statistic	Control	T2 (+150N)	T3 (+52N + GM)	T4 (+150N + WS)	(T5 + 52N + GM + WS)	T6 (+62N + FYM)	T7 (+FYM + GM)
r	−0.70	0.304	0.59	0.86	0.90	0.94	0.92
RMSE	7.09	9.684	7.26	7.42	8.70	7.12	11.07
EF	−5.98	−3.58	−0.11	0.56	0.65	0.79	0.61
CD	0.25	0.248	1.09	1.41	3.62	2.21	1.62
M	−0.38	−0.91	−0.54	−0.60	0.23	−0.30	−1.13
CRM	−0.04	−0.08	−0.05	−0.05	0.02	−0.02	−0.07

N.B.: Statistical analysis carried out using MODEVAL (Smith et al., 1997). In all cases, $n = 7$; Treatments: N: nitrogen fertilizer in t ha^{-1}; GM: green manure; WS: wheat straw; FYM: farm yard manure; Statistics: *r*: correlation coefficient; RMSE: root mean square error of model; EF: modelling efficiency; CD: coefficient of determination (best fit = 1); *M*: mean difference; CRM: coefficient of residual mass (best fit = 0).

Table 5
Quantitative statistical analysis of modelled (Century) *vs.* reported soil organic carbon data for Trial 4 in the Indian IGP

Statistic	Control	T5 N60-120-120, +FYM	T8 N60-120-120
r	−0.19	−0.34	−0.08
RMSE	19.07	35.68	21.88
EF	−16.75	−4.57	3.62
CD	0.062	0.22	0.282
M	−1.76	−4.47	−2.23
CRM	−0.16	−0.32	−0.19

N.B.: Statistical analysis carried out using MODEVAL (Smith et al., 1997). In all cases, $n = 6$; Treatments: N: nitrogen fertilizer in t ha^{-1}; FYM: farm yard manure; Statistics: *r*: correlation coefficient; RMSE: root mean square error of model; EF: modelling efficiency; CD: coefficient of determination (best fit = 1); *M*: mean difference; CRM: coefficient of residual mass (best fit = 0).

field at the time of harvest that range from 5–10%, but which are not accounted for in the reported crop production (Hanna and Van Fossen, 1990; Shay et al., 1993; Beasley, 2005; Hofman, 1978). At the highest production levels experienced at these trials, the Century model tends to reach an upper production ceiling for all three crops. This may be in part due to the necessity of rounding off each growing season to the nearest month to accommodate the time-step of the model. The constraint is especially marked for a triple cropping system such as the one found in Trial 4, reinforcing the point made earlier that further development of the Century model for triple cropping systems may be needed.

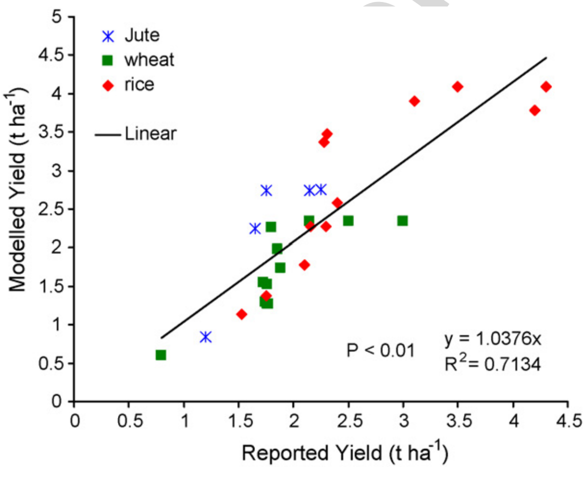

Fig. 5. Modelled *vs.* reported yield from the Century model for two long-term fertilizer trials in the Indo-Gangetic Plains, India.

5. Conclusions

This study presents a preliminary attempt to parameterise the Century model for application to rice/wheat cropping systems in two examples of varying environmental conditions found in the Indo-Gangetic Plains, India. The study indicates that Century can simulate the treatment effects of different bioclimatic systems in terms of predicting SOC change. However, the model is more successful when applied to a semi-arid site under a double cropping system, than when applied to a humid site under a triple cropping system. Century was calibrated to simulate crop yields for the two sites considered using data from across the Indian IGP. However, further adjustments may improve model performance at these sites and others in the IGP. The modifications made to the crop sub-models will help Century to simulate crop yields and SOC turnover more closely in the future for the Indian Indo-Gangetic Plains. The availability of more long-term experimental data sets (especially those involving lowland flooded rice and triple cropping systems) from the IGP, for testing and validation is critical to the application of the model's predictive capabilities for this area of the Indian sub-continent.

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