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Soil carbon balance of rice-based cropping systems of the Indo-Gangetic Plains

M.E. Shibu [a,c,d,*], H. Van Keulen [a,b], P.A. Leffelaar [a], P.K. Aggarwal [c]

[a] Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AK, Wageningen, The Netherlands
[b] Plant Research International, Wageningen University and Research Centre, P.O. Box 616, 6700 AP Wageningen, The Netherlands
[c] Indian Agricultural Research Institute, Pusa, New Delhi-110012, India
[d] Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen AB15 8QH, UK

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ABSTRACT

An agricultural land use system centred on rice-based cropping systems as common in the Indo-Gangetic Plains (IGP), with its annual cycles of wet and dry, puddling and ploughing, is unique and exerts a specific influence on soil organic matter (SOM) dynamics. Reports of yield 'stagnation' in some parts of the IGP with a decline in SOM quantity and quality raises concerns about the sustainability of the rice–wheat system in the region. Proper understanding of the soil carbon balance and of measures required to build up or maintain the soil carbon status of such a production system is therefore important for its sustainable production. Long-term experiments conducted in this region are especially useful in gaining understanding of soil carbon dynamics, since the processes affecting carbon dynamics are slow in nature. We used a simple analytical model—Yang's model—to calculate carbon balances in the rice-based cropping systems of the IGP in India. We used eight data sets from rice-based cropping systems from different sub-regions in the IGP, with different crop managements applied to rice, wheat or a third crop. Carbon input into the soil from crop biomass was calculated using data on crop yield and Harvest Index (HI). The values of soil organic carbon content predicted by the model were comparable to the observed values ($r=0.91$). The model performs well in situations with porous soils (low clay content), with a pH values in the neutral range (7–7.5) and low annual rainfall as in the situation of Ludhiana-1 and 2. However, it underperforms in situations with heavy clay soils with high rainfall, causing severe anaerobic conditions. The model projections for the long-term (by 2080) show a decline in SOC at all sites in the IGP. Hence, the yield stagnation in the IGP, which has been attributed to a decline in SOC and the associated reduction in nutrient supply, could lead to further decreases in SOC levels, aggravated by climate change-induced higher temperatures.

1. Introduction

The Indo-Gangetic Plains (IGP) of India, comprising 13% of its total area, is important in food supply for the country, contributing nearly 50% to its total food-grain production (Bhattacharyya and Pal, 2003). Crop production in the IGP is dominated by rice-based cropping systems, predominantly rice–wheat. Stimulated by an assured market, supported by government programs to sustain farm income, cropping systems in the region have strongly intensified in the last decades, through introduction of high-yielding varieties, improved irrigation facilities and abundant use of chemical fertilizers, leading to continuously increasing yields. However, recent reports (Cassman and Pingali, 1995; Duxbury et al., 2000; Gupta, 2003) suggest stagnating yield increases in some parts of the IGP under long-term intensive cultivation. A decline in soil organic matter (SOM[1]) quantity and/or quality has been suggested as one of the major causes of this yield stagnation (Dawe et al., 2000; Swarup et al., 2000; Ladha et al., 2003; Manna et al., 2005). In long-term experiments (LTEs) in rice–wheat systems in the IGP, characterized by different climate conditions, soil properties, cultivar and crop management, variable trends in SOC status have been found (Nambiar, 1995; Abrol et al., 2000). Long-term experiments of treatments without fertilizer application generally show a decline in SOC, compared to a constant or increasing SOC-content under integrated nutrient management with combined application of inorganic fertilizers and organic amendments (Katyal et al., 2001). A decline in soil organic carbon content is a common phenomenon when land use changes from natural vegetation to cropping (Jenny, 1981; De Ridder and Van Keulen, 1990; Lal, 2002). The reasons for this decline include a reduction in total organic carbon inputs, increased rate of decomposition due to mechanical disturbance of the soil, higher soil temperatures due to exposure of the soil surface, more frequent wetting and drying cycles and increased loss of surface soil, rich in organic matter, through erosion. Total above- and belowground biomass production, crop residue management (removal, burning or incorporation) and the quantities of organic amendments added to the soil, such as farmyard manure (FYM) and

* Corresponding author. Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen AB15 8QH, UK. Tel.: +44 1224 395278; fax: +44 1224 395036.
E-mail address: s.muhammed@macaulay.ac.uk (M.E. Shibu).

[1] In the remainder of this paper, organic matter content is expressed as carbon (SOC); SOM and SOC are directly proportional: $SOC = 0.58 * SOM$.

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green manure (GM), determine total organic carbon inputs. Organic carbon additions through the crop include roots, rhizodeposition (including fine roots that die and rapidly decompose, and root exudates), and crop residues. For a soil under cultivation, measures that increase above- and belowground biomass production and/or reduce removal from the field, will result in more favorable soil carbon balances (Van Wambeke, 1992; Buyanovsky and Wagner, 1998). For example, judicious application of nitrogen fertilizer increases crop yield and biomass production and thus the quantity of residues that can be incorporated into the soil (Sanchez, 1976; Singh et al., 1998; Holeplass et al., 2004). Specific soil management practices, such as minimum tillage, reduce the rate of decomposition of SOC, and consequently improve the soil carbon balance.

Long-term experiments, yielding information on seasonal or annual biomass production and carbon content in the soil are indispensable in estimating soil carbon balances, provided the experimental results can be properly interpreted, e.g. by application of appropriate process formulations. These formulations refer to mechanistic or functional relationships describing soil organic matter dynamics and crop growth. For example, data from long-term experiments conducted in Rothamsted were fundamental in constructing and validating SOM models such as RothC (Jenkinson and Rayner, 1977). In India, organized LTEs, representing different agro-climatic regions, were started in the 1970s under the All India Coordinated Research Project on Long-term Fertilizer Experiments. The main objective of these LTEs was to study the sustainability of modern high-yielding varieties under high external inputs of fertilizers and irrigation. As realization of the importance of LTEs for current and future agricultural and environmental studies increased, more LTEs were established on a regional basis, funded by state universities in the 1980s and 1990s. In the current study, data from many of these LTEs under rice-based cropping systems are compiled giving a comprehensive representation of the variation in SOC dynamics in the IGP. The objective of this paper is to use the principles underlying a simple model on SOC dynamics (Yang, 1996; Yang and Janssen, 2000) to interpret changes in soil organic carbon in rice-based cropping systems at different sites in the IGP, and to simulate possible changes in the future.

2. Methodology

2.1. Basic data

The Indo-Gangetic Plains in India, extending from Latitude 21° 45′ to 31° 0′ N and Longitude 74° 15′ to 91° 30′ E (Bhattacharyya et al., 2004), can be divided into 4 sub-regions: Trans-Gangetic Plain (TGP), Upper-Gangetic Plain (UGP), Middle-Gangetic Plain (MGP) and Lower-Gangetic Plain (LGP). We compiled and used 8 data sets of LTEs, covering up to 30 years of cropping under rice-based cropping systems in the different sub-regions. Climate and soil characteristics of the various sites are given in Table 1. The LTEs cover a range of treatments, including different doses of chemical fertilizers, green manures, and farmyard manure, and different residue management practices applied to rice, wheat and/or a third crop (Table 2). Although consistency in treatments applied to different sites could be ascertained in all these LTEs, some degree of inconsistency in data collection, associated with changes in field staff and/or laboratory technicians is unavoidable, as these experiments often span the lifetimes of several researchers. However, such 'human errors' cannot be quantified with the limited information available about these experiments and need to be accepted as part of the measured system.

2.2. Yang's model

Soil organic matter dynamics can be described through Yang's equation (Yang, 1996; Yang and Janssen, 2000; Yang and Janssen, 2002):

$$Y_t = Y_0 e^{\left(-R_9 (ft)^{1-S}\right)} \tag{1}$$

where Y_0 and Y_t are the mass fractions of C in soil (g kg^{-1}) at time t = 0 and t year, respectively; R_9 is the average relative decomposition rate between t = 0 and t = 1 at 9 °C; *f* is the temperature correction factor that modifies the time component (the product *ft* is comparable to *physiological time*, as a fixed heat sum is required to decompose a unit of SOC) in the equation; and S is a dimensionless factor that represents the speed of ageing of the substrates. In our study, the value of *f* was calculated from the mean annual temperature (T) at the site. For the temperature range of 9–27 °C (Table 1), the f value is calculated as $2^{(T-9)/9}$. For temperatures above 27 °C, *f* is set to a constant value of 4 (Noij et al., 1993; Yang, 1996).

Table 3 gives average values of R_9 and S, derived by Yang for major organic materials used in agriculture. The model was previously applied to predict long-term SOM dynamics in arable lands in Northern China (Yang and Janssen, 1997) to suggest measures for maintenance and/or improvement of SOC content. The R_9 and S values for rhizodeposition, which were not provided by Yang (1996), were estimated for the current study based on the following reasoning: rhizodeposition mainly consists of root exudates, i.e. organic acids. These simple organic molecules decompose more easily than the other organic materials mentioned in Table 3. Since substrates with high R_9-values also have high S-values (Yang, 1996), upon consultation with one of the developers of Yang's model, we estimated the values for R_9 and S for rhizodepostition about 10% higher than those for green manure.

2.3. Sensitivity analysis

Sensitivity of these model parameters (*R_9* and *S*), variations in the source and amount of organic inputs and environmental (temperature) factors to SOC status was analyzed by running the model over a plausible range of values. To this purpose, we have varied three variables: temperature (±3 °C), R_9 and S (±20%) independently and

Table 1
Soil* and climatic characteristics of the various sites used in the study.

Sites	ACZ	Texture class	Soil type	Clay %	MAT °C	MAR mm	pH	BD kg m^{-3}	SOC g kg^{-1}	Reference
Ludhiana-1	TGP	Loamy sand	Typic Ustipsamment	12.6	22	800	7.6	1550	3.6	Yadvinder et al., 2004a
Ludhiana-2	TGP	Loamy sand	Typic Ustipsamment	10.9	22	800	7.2	1550	3.5	Yadvinder et al., 2004b
Ludhiana-3	TGP	Loamy sand	Typic Ustochrept	12	22	800	8.2	1550	3.8	Bhandari et al., 2002
Karnal	TGP	Sandy loam	Aquic Natrustalfs	15	23	766	8.7	1550	4.0	Yaduvanshi, 2001
Pantnagar	UGP	Silty clay loam	Aquic Hapludoll	20	22	1400	7.3	1320	14.8	Ram, 1998; Ram, 2000
Samastipur	MGP	Sandy loam	Not available	17	26	1204	8.5	1500	5.1	Prasad and Sinha, 2000
Barrackpore	LGP	Sandy loam	Eutrochrept	18	26	1666	7.1	1300	7.1	Saha et al., 1998; Saha et al., 2000
Nadia	LGP	Sandy loam	Not available	16.5	27	1490	7.5	1300	9.4	Samui et al., 1998; Kundu and Samui, 2000

ACZ: Agro-Climatic Zone; MAT: Mean Annual Temperature; MAR: Mean Annual Rainfall; BD: Bulk Density; SOC: Soil Organic Carbon; TGP: Trans-Gangetic Plain; UGP: Upper-Gangetic Plain; MGP: Middle-Gangetic Plain; LGP: Lower-Gangetic Plain.
* Soil characteristics correspond to 0–15 cm depth for all the sites except Barrackpore where the depth is 0–23 cm.