Modeling long-term dynamics of carbon and nitrogen in intensive rice-based cropping systems in the Indo-Gangetic Plains (India)

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Modeling long-term dynamics of carbon and nitrogen in intensive rice-based cropping systems in the Indo-Gangetic Plains (India)

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Dedicated to my late parents

A PRAYER

Where the mind is without fear and the head is held high
Where knowledge is free
Where the world has not been broken up into fragments
By narrow domestic walls
Where words come out from the depth of truth
Where tireless striving stretches its arms towards perfection
Where the clear stream of reason has not lost its way
Into the dreary desert sand of dead habit
Where the mind is led forward by Thee
Into ever-widening thought and action
Into that heaven of freedom, my Father, let my country awake

Rabindranath Tagore
(Nobel laureate, 1913)

Abstract

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Soil organic matter (SOM) is an essential component of any sustainable crop production system, both as a nutrient source for the crop and a physical conditioner for the soil. Land use systems based on (flooded) rice- aerobic upland crop rotations, with their annual cycles of wet and dry soil conditions, puddling and plowing, are unique in their influence on SOM dynamics. Recent reports have related yield ‘stagnation’ in rice-wheat systems in parts of the Indo-Gangetic Plains (IGP) to a decline in SOM quantity and quality. For exploration of the long-term effects of intensive cultivation on soil C and N dynamics, and the consequences for crop yields, a summary model has been developed, based on insights in the underlying processes, to investigate the role of soil organic matter in yield formation in rice-based cropping systems in the IGP and to identify possible reasons for declining yields in the region.

Following a review of existing SOM models with emphasis on approaches and principles, to identify processes relevant for long-term dynamics of C and N in rice-based cropping systems, the different components of the systems (SOM and crop) were investigated. A simple analytical model (Yang’s model) used to analyze soil carbon balances for different sites in the IGP, showed that carbon demand to maintain soil organic carbon (SOC) levels depends on their initial level, and SOC dynamics are governed by crop performance, determining the rate of carbon input into a soil, and the carbon input through organic amendments. A crop growth model (LINTUL3) was developed describing crop growth of rice for N-limited situations. Nitrogen stress in the model is quantified through the nitrogen nutrition index, a measure of relative crop (leaf and stem) nitrogen content. Subsequently, the knowledge was integrated into a summary model, comprising three modules: a soil organic matter (SOM) module, a soil (SOIL) module, and a crop growth (CROP) module. SOM in the model comprises three pools: fresh, labile and stable. Carbon and nitrogen dynamics in the model are described in terms of carbon turnover, assimilation and dissimilation, with nitrogen linked through distinct C/N ratios. Turnover of fresh SOM depends on substrate composition. Maximum relative turnover rates of the labile and stable pools are pool-specific and actual rates are influenced by environmental (temperature, moisture, texture, pH) and management (tillage and puddling) factors. Data sets of nine long-term experiments from the IGP of India were used to calibrate and validate the model. In general, the model satisfactorily reproduced observed crop yields, SOC dynamics and total soil N dynamics for various cropping systems at different sites. With recommended fertilizer NPK applications, a significant decline in yield was found only at two sites: Ludhiana-3 and Pantnagar. Nitrogen mineralized from soil organic matter contributed 20-80% to total N uptake for different treatments. The model results show that an increase in SOM is not always associated with an increase in yield, as the factor(s) improved by an increase in SOM may not be the limiting factor for crop growth. The study concludes that SOM is not always a direct measure of a soil's nitrogen supplying capacity and the importance of SOM as a nutrient source for the crop depends on the relative contribution of other N sources. This suggests that SOM dynamics are not the sole reason for observed yield stagnation.

Keywords: Soil organic carbon, soil organic nitrogen, wheat, yield decline, Yang's model, crop growth, nitrogen nutrition index.

Preface

When I was learning the basics of agriculture during my Bachelor with crops and crop management, I thought agricultural research was confined to only field and laboratory experiments. The idea of modeling was not even heard at that time as it was never a part of our curriculum. In the last year of my BSc, we got introduced to the basics of computer programming (BASIC), which was included in the curriculum at that time. A little knowledge in programming, made me to think that we could use computers in agriculture in some decision making process. Later, during my master's study with specialization in soils at Punjab Agricultural University (PAU), Ludhiana, I have followed some more programming languages with the same interest, but knowledge about modeling was still far away. After my MSc., while looking for job opportunities, I ended up in the Centre for Applications of Systems Simulation (CASS) in Indian Agricultural Research Institute, New Delhi, by joining in a project under Dr. P. K Aggarwal as a Research fellow. Dr. P.K. Aggarwal introduced me to the basic concepts of modeling, gave me two weeks training in systems, simulation and modeling (a course organized by CASS), and I got the opportunity to work with DSSAT and WOFOST crop/cropping systems models. Immediately, I realized that yes, this is what I was looking for!

Dear Aggarwal sir, thanks for trusting me when I was a novice to this field and giving me the needed support to learn and the patience to teach me. The network of PK, as he is called in his known circles in Wageningen, made to think of a sandwich PhD project with Wageningen University on rice-based cropping systems and I was introduced to Prof. Herman van Keulen. We made few initial correspondences through e-mails until I reached here in October 2002, six months later than initially planned. On the first day of arrival in Wageningen, I met dr. ir. Peter Leffelaar, who became my co-promoter. The sandwich plan was to spend 6 months in the Netherlands and 6 months in India in the next three years and the last year again in the Netherlands. This arrangement made me to go through the worst climates on the two sides of the same hemisphere: the harsh winter in the Netherlands and the hot summer in India.

In Wageningen, working very closely with Herman and Peter was a continuous learning experience. I love the meetings we used to have at least once every fortnight. No need to mention that how useful and productive they were for my research. Apart from that, these meetings increased my vision and knowledge about agriculture and science as a whole, as Herman shares his vast experience with us. Dear Herman, I will never forget many of your scientific jokes, *Panda eats, shoots and leaves from a pub*; *the discrepancy between the model results and the observations is because the sheep did not read the theory*; and your regular quotes like *life is difficult… as it is meant to be.* Herman, your contribution to this study was immense and without that, this effort would not have culminated in this book.

From Peter, apart from science, I learned many things, especially how to organize myself to be systematic and consistent. You always warned me to take back up of my work. You kept saying that ‘in science, don’t believe anyone and be critical of everything’. Dear Peter, you worked with me even during the weekends and holidays at the last phase of preparing this manuscript. You were always out there to help me whenever I approached you with my all range of problems. Recently, when I lost my apartment’s key, you taught me how to ‘manage’ and walked with me to overcome that emergency situation.

Herman and Peter, both of you have edited my manuscripts several times to make it more understandable to people other than we three. Still many times, I missed the prepositions in my sentences. I know I need to improve a lot in that area.

I would like to acknowledge and thank NWO-WOTRO for funding my PhD project. I would also like to extend my sincere thanks to many people who were working in different research institutes in India (Dr Bijay Singh, Dr.Yadvinder Singh, Dr. D.K. Benbi, and Dr. B.S. Ghuman from PAU, Ludhiana; Dr. M.N. Saha from Central Research Institute for Jute and Allied Fibres, Barrackpore, Dr. B. Mishra from Pantnagar University of Agriculture and Technology; Pantnagar; Dr. P.K. Sharma from Palampur Agricultural University, Palampur; Dr. A.L Kundu from Bidan Chandra Krishi Vishwa Vidyalaya, Mohanpur; Dr. N.P.S. Yaduvanshi from Central Soil Salinity Research Institute, Karnal) for their willingness to share the data and informations pertaining to their long-term experiments and for their hospitality.

I would like to extend my sincere thanks to Gon van Laar for her help to prepare the lay out of this book. I appreciate her willingness to help PhD students to get through this last phase. Special thanks goes to Bert Janssen for his valuable comments and suggestions on Chapter 2 and 3. I acknowledge the help and suggestions of Joost Wolf whenever I approached him with some questions.

Working in Plant Production Systems (PPS) was a pleasant experience. Very cordial and helpful scientists as well as office staffs and students made the ‘difficult’ life sometimes easier. I thank Dr. Ken Giller for providing such a wonderful working atmosphere and the facilities. Ken, thanks for your invitations to your house during the last few New Years and many other similar occasions. I appreciate your hospitality and the friendly attitude. I thank our office staffs, Ria van Dijk, Charlotte Schilt and Gijsbertje Berkhout and Sjaak Tijnagel for their sincere assistance, without that, life of an international student would have been stuck in a bureaucratic network. I express my gratitude to Bert Rijk, Eelco Meuter, Marcel Lubbers and the staff from TUPEA for their operational help with computers and software. A regular social event, which I am going to miss when I leave Wageningen is the dinner at Nico's place. 'International' recipes, cooking and dining together at every now and then with PhD students was a wonderful experience. I thank Nico and Rieta and urge them to keep this tradition go on.

Wageningen has a 'dynamic' society. Every year, I see some new people and I do not see some people I saw already. I would like to thank many people I came across with in the last four years; with whom I shared some good moments, ideas and knowledge. Among them few names I cannot leave without mentioning: Regis Chikowo, Assefa Abegaz, Freddy Bijukia, Santiago Lopez, Paul Belder, Mahmoud Otroshy, John Ojiem, Bongani Ncube, Mai van Trinh, Shamie Zingore, Bhayyasaheb Patil, Pablo Tittonell, Myrium Adam, Ilse Geijzendorffer, Rik Schuiling, Mark van Wijk, Eduardo Cittadeni, Fernando Funes Monzote, Benjamin Kibor and Chrispen Murungweni.

When one is away from home, one tries to find home with your fellow country mates. Yes, I cherish the time I spent with my fellow Indians in Wageningen by cooking, playing, dancing and laughing. I got some valuable friendships such as Ranvir (and Gina), Basav, Shital, Ganesan, Kishore, Senthil, Arun, Byjesh, Srinivas, Aarti, Anand, Sharad, Bobby, Palwinder Bhaisaab, Ram, Ajay and Sangeeta. My special thanks to Kishore and Byjesh for assisting me in preparing the list of references during the last days of my thesis submission. I thank all my 'Indian' Wageningen friends for their support and encouragement. I also appreciate the friendship of Freek who visited me in India and stayed with my family.

I also thank MSc. students in the PPS group: Jéróme, Yann, and Solenn, for their company during lunch time. I also thank Maria and Aneta for our weekend meetings, drinks and the dinner.

I also thank my friends in India who were helping and supporting me in my all difficult times, especially when I was hospitalized. I thank Shabih and Burhan for taking care of me at hospital. I also thank Binay, my old classmate, for providing me the food and shelter during my visit in PAU.

I normally do not thank my family as they were always with me; my ups and downs were their’s too. Without their support, I may not have reached at this point. I remember my late parents at this moment, and I thank my brothers and sisters for not allowing me to feel the gap of my parents.

At last, I thank all of you whom I remember, but did not include in these few pages for bringing me a smile on my face at some point of my stay in Wageningen or in India. I wish you all the best!

Contents

CHAPTER 1

General introduction

Introduction

Pre-independent India had a long tradition of declining per capita food production with repetitive droughts, food shortages and even famines. After independence in 1947, food security was given high priority in policy planning. Until 1967, the efforts to increase food grain production by policy makers were largely concentrated on increasing the area under cultivation. However, the rate of increase in cultivated area and in food grain production per hectare were not sufficient to cope with India's growing population. After 1967, the 'Green Revolution' (1967-1985) resulted in the introduction of new high yielding varieties, development of new irrigation facilities, and high inputs of fertilizers and pesticides in India's agricultural sector. As a result, food grain production increased from 68 Tg[1] in 1955 to 150 Tg (Figure 1) in 1985 (Singh, 1999; Directorate of Agricultural Statistics, 2004). By applying technologies developed during and after the green revolution, India became a food self-sufficient country in the 1990s. The rate of growth in food production (1.9% annually) was about equal to the rate of population growth (1.85%) during these years and surplus production was reported in many years, with food grain buffer stocks mounting up to 60 Tg in 2001. At present, a net area of 142.5 Mha (43%) out of the total (geographical) area of 329 Mha is under cultivation in India. Nearly 87% of this area is under food grain crops, of which rice (34%) and wheat (21%) are the most important, accounting for 75 percent of the total food grain production in 2003-2004. The Indo-Gangetic Plains (IGP), the cradle of the green revolution in the 1960s and covering an area of 44 Mha, is the most important food-producing domain of India. Its abundant natural resources, i.e. deep, productive soils, with good quality surface- and groundwater, favorable climatic conditions for multiple cropping seasons per year, with crops such as rice and wheat, has played a key role in realizing the food grain production level needed to sustain a burgeoning population. In the past decades, rice-based cropping systems have emerged as the major cropping system in the IGP, with rice-wheat rotations as the major system. At present, the IGP contributes nearly 42 percent to the total food grain production in the country.

More than 40 years after the green revolution, the still increasing population of the country, at a rate of 2 percent annually, continues to pose challenges to agriculture to maintain food security. At the current growth rate, population is expected to grow to 1.6 billion by 2050 (Cassen and Visaria, 1999) and food grain demand to 290 Tg (Bandyopadhyay, 2001), i.e. an increase by almost 40 percent. At the same time, agriculture faces increasing competition for land, water and other natural resources from other sectors, such as industry and the private sector. Therefore, producing more

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[1] Tg= 10^{12} g

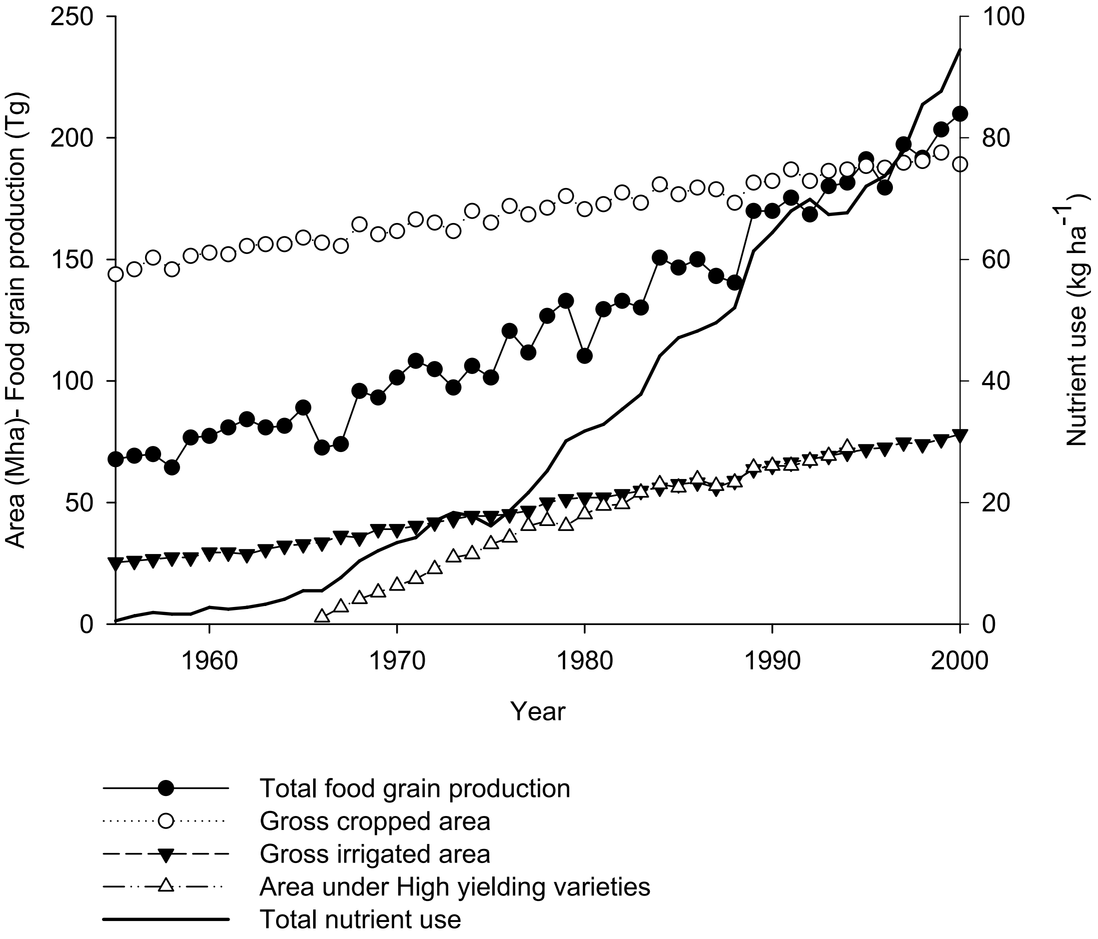

Figure 1. Growth of major production factors and food grain production in India (adapted from Singh, 1999 and Directorate of Economics and Statistics, 2004).

to meet the demands of the growing population for food, fibres, feed for animals, raw materials for industry, maintaining buffer stocks and export of food grains remains a challenge, especially for intensively cultivated areas, whose sustainability is already threatened. Since increasing the area under food crops is no longer an option and more and more land is lost to non-agricultural purposes and to land degradation, the increase in food demand should be realized by increasing yields from the existing land resources.

To meet the long-term goals of agriculture, outlined in the preceding paragraph, sustainability is a prerequisite. Intensive cultivation with high water-demanding crops has led to a decrease in groundwater levels, serious water logging and secondary salinization in large parts of the IGP (Rai, 2002; Ladha et al., 2003). Moreover, leveling off of the yield increase, declining input factor productivity and even declining crop yields have been reported for parts of the IGP (Ram, 1998; Dawe et al., 2000; Duxbury et al., 2000; Narang and Virmani, 2001; Ladha et al., 2003). One of the major reasons put forward for such stagnation in yield is the decline in soil organic matter (SOM) quality and quantity (Dawe et al., 2000; Yadav et al., 2000; Ladha et al., 2003). Other reasons include nutrient imbalances, reduced solar radiation and increased incidence of pests and diseases. As soil organic matter plays such a key role in production capacity and thus is one of the major indicators of sustainability of any cropping system, the present study focuses on its two major components, carbon and nitrogen, with special attention for their long-term dynamics in the rice-based cropping systems in the IGP of India.

Description of study area: the Indo-Gangetic Plains (IGP) of India

The Indo-Gangetic Plains (IGP) in South Asia stretches from the Indus river system in Pakistan to the Punjab Plain (both in India and Pakistan) and from the Haryana Plain to the Delta of the Ganges in Bangladesh (Figure 2). The name *Indo-Gangetic Plains* is derived from the two river systems in the region *Indus* and *Ganges*. The IGP of India extends from 21°45' to 31°0' N latitude and from 74°15' to 91°30' E longitude and in India includes the states of Punjab, Haryana, Delhi, Himachal Pradesh, Uttar Pradesh[2] and the northern parts of Rajasthan and Tripura, covering a total area of 43.7 Mha, i.e. 13% of the total area of the country. The IGP is one of the three tectonic divisions of mainland India, next to the Greater Himalayas and its associated mountains, and the ancient Deccan Plateau (Narang and Virmani, 2001). It was formed as a result of continuous deposition of alluvium from the Himalayas in the North and the hill ranges of Deccan in the South. In the Punjab Plains, the sediments have been deposited by the rivers Ravi, Beas, and Sutlej originating in the Shivalik Himalayas. The Ganges Plain has been formed through sediment deposition from the rivers Ganges, Yamuna, Ghagara, Gandak and Gomati, also originating from the Himalayas. Two narrow terrain belts, collectively known as *terai*, constitute the northern boundary of the IGP at the foothills of the Himalayas. The southern boundary of the plain begins along the edge of the Great Indian Desert in the state of Rajasthan and continues east along the base of the hills of the Central Highlands to the Bay of Bengal.

Physical environment

Based on the criteria of homogeneity in agro-climatic characteristics, soil type, and physiographic features, within the IGP four Agro-Climatic Regions (ACRs)[3] have been distinguished (Planning Commission, Government of India, 1979).

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[2] Uttar Pradesh state includes the parts of IGP in the newly formed state of Uttaranchal.

[3] Recently more areas (parts of Himachal Pradesh, parts of Tripura) have been included in the IGP (Velayutham et al., 1999), but these are not included in this classification.

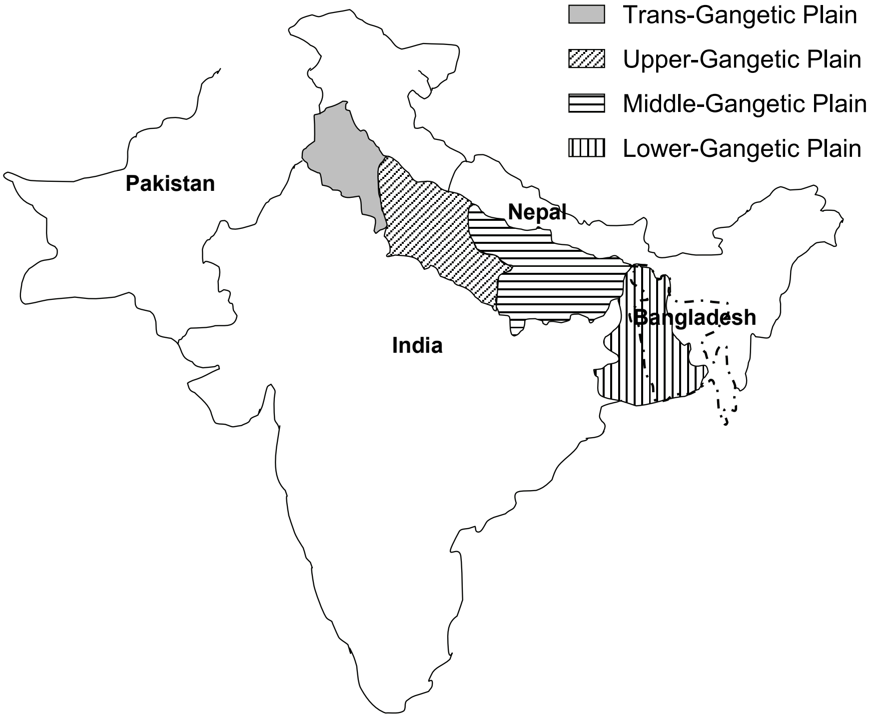

Figure 2. Map of the IGP showing Trans-, Upper-, Middle-, and Lower- Gangetic Plains.

1. TGP-Trans-Gangetic Plains (Punjab, Haryana, and parts of Uttar Pradesh)
2. UGP-Upper-Gangetic Plains (Uttar Pradesh)
3. MGP-Middle-Gangetic Plains (Most of Bihar, and parts of Uttar Pradesh)
4. LGP-Lower-Gangetic Plains (Most of West Bengal)

Climate

Climate in the IGP is dominated by the Asian summer monsoon (White and Rodriguez-Aguilar, 2001), but varies strongly, going from west to east. The western part of IGP (TGP and UGP) is characterized by a semi-arid climate with mean annual rainfall of 500-800 mm, whereas the eastern part (MGP and LGP) is characterized by a humid climate with mean annual rainfall ranging from 1500-3200 mm. Mean annual temperature in the IGP varies from 22 to 27 °C. Summer temperatures are generally higher in the northwestern part, reaching daytime temperatures as high as 45 ^{0}C in June-July, whereas in winter temperatures may be as low as 4 °C. In the eastern parts of the IGP, maximum temperatures in summer reach 38 °C and minimum temperatures in winter may be as low as 10 °C (White and Rodriguez-Aguilar, 2001).

Table 1. Description of the Agro-Ecological Regions (AER) and Sub-Regions (AESR) in the IGP of India (Source Bhattacharyya et al., 2004).

AER No. / AESR No.	AER/ AESR	Characteristics	MAT ($^{\circ}$C)	MAP (mm)	States/districts	Area (Mha)
2	*Western Plains*	*Hot arid, GP < 60 days*				*3.112*
2.1	Marusthali Plains	Hot hyper-arid, low AWC, GP < 60 days	27	218	Punjab, Rajasthan	0.358
2.3	Kachch Peninsula	Hot hyper-arid, low AWC, GP < 60 days			Punjab, Haryana	2.754
4	*Northern Plains*	*Hot semi-arid, GP 90-150 days*				*13.265*
4.1	North Punjab Plain, Ganga-Yamuna Doab	Hot semi-arid, medium AWC, GP 90-120 days	25	700	Punjab, Haryana, UP	7.599
4.3	Ganga-Yamuna Doab, Rohilkhand and Avadh Plain	Hot moist semi-arid, medium to high AWC, GP 120-150 days			UP	5.666
9	*Northern Plains*	*Hot sub-humid (dry), GP 120-180 days*				*9.763*
9.1	Punjab and Rohilkhand Plains	Hot dry to moist sub-humid transition, medium AWC and GP 120-150 days	25	800	Jammu and Kashmir, HP Punjab, Haryana, UP	3.630
9.2	Rohilkhand, Avadh and South Bihar Plains	Hot dry sub-humid, medium to high AWC and GP 150-180 days			UP, Bihar	6.133
13	*Eastern Plains*	*Hot sub-humid (moist), GP 180-210 days*				*10.219*
13.1	North Bihar and Avadh Plains	Hot dry to moist sub-humid with low to medium AWC and GP 180-210 days			UP, Bihar	8.778
13.2	Foothills of the Central Himalayas	Warm to hot moist, high AWC and GP 180-210 days	22	1500	UP	1.441
15	*Bengal Plains*	*Hot sub-humid to humid, GP 210-300 days*				*6.641*
15.1	Bengal Basin and North Bihar Plains	Hot moist sub-humid with medium to high AWC and GP 210-240 days	26	1500	West Bengal, Bihar	5.861
15.3	Teesta, Lower Brahmaputra Plain	Hot moist humid to per-humid medium AWC and GP 270-300 days	25	2000-3200	West Bengal, Tripura	0.780
16	*Eastern Himalayas*	*Warm per-humid, GP 270-300 days*				*0.216*
16.1	Foot-hills of the Eastern Himalayas	Warm to hot per-humid, low to medium AWC and GP 270-300 days	23	2600-3000	West Bengal	0.100
16.2	Darjeeling and Sikkim Himalayas	Warm to hot per-humid, low to medium AWC and GP 270-300 days	14	>2500	West Bengal	0.116
17	*North –Eastern hills (Purvachal)*	*Warm per-humid, GP> 300 days*				*0.082*
17.2	Purvachal (Eastern range)	Warm to hot, per-humid, low to medium AWC and GP >300 days	22	>3000	Tripura	0.082
18	*Eastern Coastal Plain*	*Hot moist sub-humid to semi-arid, GP 240-270 days*				*0.393*
18.5	Gangetic delta	Hot moist, sub-humid to humid, medium AWC and GP 240-270 days.	26.7	1900	West Bengal	0.393

MAT: Mean annual temperature; MAP: Mean annual precipitation; GP: Length of potential growing period of a crop; AWC: Available water capacity; UP: Uttar Pradesh HP: Himachal Pradesh.

Relief

Elevation in the IGP-India varies from 0 m to 330 m above mean sea level (Velayutham et al., 1999).

Soils

Soils of the IGP are generally alluvial, but with variations in the upland and lowland areas. The alluvial sediment of the IGP is quite thick and particle size distribution is dominated by silt size fractions. The vast alluvium has been classified into two groups:

1. Older alluvium: fine-textured, dark-colored, calcareous with pronounced pedogenic activity.
2. Younger alluvium: coarse-textured, light–colored, with little or no pedogenic activity.

Moving from west to east in the IGP, soil texture becomes more clayey, resulting in decreased drainage.

Agro-ecological classification

Based on physiography, soils, climate, growing period and available water holding capacity of the soils, India has been classified into 20 agro-ecological regions (AERs) (Sehgal et al., 1992; Velayutham et al., 1999). Mapping and classification of AERs is based on an overlay of four base maps: physiography, soils, bioclimate, and length of growing period (GP). In the IGP, 8 of these AERs occur: 2, 4, 9, 13, 15, 16, 17 and 18 (Table 1). These 8 AERs have been sub-divided into 14 agro-ecological sub-regions (AESR), based on detailed soil information at sub-group level, physiography at land form level, bioclimate and GP at 30-day intervals.

Land use: rice-based cropping systems

Rice-wheat

Rice-wheat cropping systems occupy about 7.15 Mha (66%) of the total area of 10.81 Mha of rice-based cropping in the IGP (Table 2) (Yadav and Subba Rao, 2001). The largest area of the rice-wheat rotation is found in TGP, followed by MGP and UGP, while it occupies a small area in LGP (0.23 Mha), mostly including other crops, such as summer rice, jute, gram and vegetables in the rice-wheat sequence. Rice and wheat are both nutrient-demanding crops and the rice-wheat cropping system annually removes 270-680 kg ha^{-1} of N, P and K combined, depending on production level, soil type and residue management (Singh et al., 2003).

Table 2. Area (Mha) under various rice-based cropping systems in the IGP of India.

	TGP	UGP	MGP	LGP	Total
Rice-wheat	2.62	2.06	2.43	0.04	7.15
Rice-wheat-other crops	-	-	-	0.14	0.14
Rice-wheat-pulses	-	-	-	0.05	0.05
Rice-fallow	-	-	1.03	-	1.03
Rice-vegetables-summer rice/jute	-	-	-	0.94	0.94
Rice-potato/vegetables-summer rice	-	-	0.02	0.58	0.60
Rice-pulses	-	0.04	0.43	0.02	0.49
Rice-mustard-jute/summer rice	-	-	-	0.36	0.36
Rice-sugarcane	-	-	0.05	-	0.05

TGP: Trans-Gangetic Plain; UGP: Upper-Gangetic Plain; MGP: Middle-Gangetic Plain; LGP: Lower-Gangetic Plain (Yadav and Subba Rao, 2001).

Rice-vegetables

The rice-vegetable cropping system is practiced mainly in the state of West Bengal in the LGP. Rice-vegetables-summer rice/jute is the third largest (0.94 Mha) cropping system of the IGP after rice-wheat and rice-fallow (Table 2). The major vegetables grown in sequence to rice are chilli, onion, melon, cucumber, and garlic (Tripathi et al., 1997).

Rice-potato

The rice-potato (including rice-potato-vegetables and rice-potato-summer rice) cropping system is another major cropping system in the LGP, covering an area of 0.58 Mha (Table 2). The system is found in very small areas of Bihar and Eastern Uttar Pradesh and also in the MGP. In West Bengal, rice-potato-rice is a more suitable cropping system than rice-wheat. This cropping system has the advantage of two crops of rice a year without delaying planting of potato.

Rice-pulses

Major pulse crops grown in the region include chickpea, lentil, pigeon pea, black gram, mung bean and pea. The largest area under rice-pulses (0.43 Mha) system is found in the MGP. Small areas under rice-pulses and rice-wheat-pulses are found in LGP (0.07 Mha) and UGP (0.04 Mha). Including legumes in cereal-based cropping systems, such as rice-pulses and rice-wheat-pulses, increases cereal productivity and improves soil nitrogen status.

Production constraints in the rice-based cropping systems

Yield trend analyses of long-term experiments on rice-based cropping systems of the IGP have shown a decline/stagnation in yields at some sites, especially for rice (Cassman and Pingali, 1995; Duxbury et al., 2000; Narang and Virmani, 2001; Bhandari et al., 2002). Duxbury et al. (2000) showed that in 8 out of 11 long-term (more than 8 years) rice-wheat experiments in India and Nepal rice yields in the highest yielding treatments declined and in three cases wheat yields declined. Such observations have raised concerns about the long-term sustainability of the intensive rice-based cropping systems. Many reasons (Table 3) have been suggested for this yield decline/stagnation. Major reasons for yield decline in the IGP include:

Decline in SOM-content: An emerging concern in R-W systems is the reduction in SOM-content and the associated reduced nutrient supplying capacity. Nambiar (1995) reported that SOM in treatments not receiving farmyard manure (FYM) declined in some long-term experiments (LTEs) in India, and that applications of FYM before either crop were effective in building up SOM and boosting crop yields. In the present rice-based cropping systems, crop residues are either burnt or removed from the field for stock feed and bedding, roofing and fencing. The traditional practice in many places of the IGP of burning rice straw after harvest is causing large losses of N (80%) (Raison, 1979), P (25%), K (21%) (Ponnamperuma, 1984) and S (Lefroy et al., 1994) and significant air pollution. On the other hand, when residues are incorporated into the soil, mineral nitrogen is immobilized during decomposition, which may reduce nitrogen uptake and yield of the succeeding wheat crop by about 40% (Sidhu and Beri, 1989), whereas the combined use of rice or wheat straw and inorganic fertilizer in R-W systems can increase the yield of rice and wheat (Mahapatra et al., 1991).

Changes in SOM quality: Various studies (DeBusk and Reddy, 1998; Dobermann and Witt, 2000) have reported more accumulation of organic carbon in continuously flooded rice systems than in upland systems. Accumulation of organic matter in continuous rice systems is due to reduced decomposition and lignin degradation under anaerobic conditions, resulting in enrichment of young humus with phenolic compounds. Increasing the number of annual irrigated rice crops and thus reducing the length of the aerobic period, increased the phenolic nature of the humic acid fractions in the soil (Olk and Cassman, 1995; Olk et al., 1996; Olk et al., 1998) and caused a decline in native soil N supply and yield (Cassman et al., 1998). Very few studies (Olk et al., 1996; Bronson and Hobbs, 1998; Olk et al., 1998) have attempted to elucidate the qualitative changes in SOM under flooded rice-upland cropping systems.

Table 3. Suggested reasons for declining yields in long-term experiments of rice-based cropping systems in the IGP.

Reasons	Site	References
Decline in soil C and N	Pantnagar	Ram, 2000; Dawe et al., 2000; Ladha et al., 2003
	Barrackpore	Saha et al., 2000; Dawe et al., 2000
Change in SOM quality	-	-
Decrease in solar radiation	Ludhiana	Bhandari et al., 2002; Pathak et al., 2003
Increase in min. temperature	Ludhiana	Pathak et al., 2003; Ladha et al., 2003
Decline in soil N, P and K	Ludhiana	Bhandari et al., 2002; Yadvinder et al., 2000
Decline in soil Zn	Pantnagar	Ram, 1998; 2000
Delay in wheat sowing	Ludhiana	Ortiz-Monasterio et al., 1994

Negative (macro and micro) nutrient balances: In general, soil nutrient balances in the region are negative, due to inappropriate fertilizer applications. Even though N fertilizers are applied at recommended levels to the crops, soil N-balances are generally negative (Dawe et al., 2000; Bhandari et al., 2002; Ladha et al., 2003). Integrated nutrient management, including application of organic amendments was found to improve the nitrogen status of soils. In general, soil P-balances are positive when P is applied at the recommended rate. At the recommended levels of fertilizer application, soil K-balances are strongly negative at many sites under study (Yadav et al., 1998; Regmi et al., 2002; Ladha et al., 2003). In the north-western regions of the IGP that are characterized by illite clay minerals, rich in K, farmers generally do not apply K, resulting in strongly negative soil K balances due to crop uptake.

Modification of physical properties: A major issue related to soil management in rice-based cropping systems is the negative effect of land preparation, including puddling, for the rice crop on soil physical properties and the associated delay in planting of the succeeding crop. The traditional technique of rice cultivation, which includes puddling of the soil to form a water-saturated root zone for the easy establishment of seedlings, suppression of weeds and reduced seepage of standing water, breaks the capillary pores, reduces the void ratio, destroys soil aggregates, disperses fine clay particles, and lowers soil strength in the puddled layer (Sharma and De Datta, 1996). In the process of puddling, clay particles fill the macro pores at greater depth (15-30 cm), resulting in a compacted layer over the years. In such soils, rice roots are largely confined to the puddled layer and few penetrate below 20-cm depth. The ‘aerobic crop’ following rice, for example wheat, faces a number of soil physical problems, such as the degraded soil structure and the compacted layer, which forms a hard pan of increased strength on drying (Meelu et al., 1979; Prihar et al., 1985; Gajri et al., 1992; Aggarwal et al., 1995). The destruction of soil aggregates during puddling results in formation of surface crusts and cracks on drying, which delays the preparation of a seedbed for the succeeding crop. In rice-wheat systems, any delay in wheat planting after the end of November results in 1-1.5% yield loss per day (Ortiz-Monasterio et al., 1994). Delay in planting occurs after a late harvest of the rice crop or because of a longer time needed to prepare the seedbed.

Organic matter and its role in sustainable agricultural production systems

Soil organic matter plays an important role in many physical, chemical and biological processes through its influence on soil structure, soil water holding capacity, cation exchange capacity, its ability to form complexes with metal ions and as a nutrient source and store. Proper management of SOM is important to food security and the protection of marginal lands (Scherr, 1999). In general, SOM contents decrease under farming. Soil organic matter content can fall to as low as 30%, but most commonly it falls to about 60% of that found under indigenous vegetation within an average of 10 years of arable farming (Brown, 1994). Although tropical conditions favor SOM decline, its level seldom reaches a stage of complete exhaustion. Rather, SOM-levels in cultivated soils tend to attain a steady state, described as a lower equilibrium limit by Buyanovsky and Wagner (1998). There is also an upper limit for SOM that is the equilibrium content typical for a virgin ecosystem. If SOM loss by erosion is negligible, then SOM level in a properly managed soil fluctuates between these two extremes. Cultivation alone tends to stabilize the SOM at the lower equilibrium level. But SOM additions and fertilizer applications tend to shift the equilibrium towards the upper limit. Buyanovsky and Wagner (1998) reported a decline in native SOM between 20-40% within five years after cultivating a virgin land and the loss continued till the lower equilibrium of 30% of the original SOM level was reached. However, return of organic residues keeps the equilibrium at a higher level. Many soil, climatic and management factors also influence this equilibrium. With the same input of organic material in terms of quantity and quality, clay soils contain more organic matter than sandy soils (Jenkinson, 1988). The degree of physical protection of organic material to microbial attack appears to increase with the clay content of the soil. There is always an inverse relationship between SOM content and mean annual temperature (Jenny and Raychaudhury, 1960; Jenny, 1980). As for many other biological processes, the rate of decomposition will increase by a factor of two with every 10^0C rise in temperature. Soil management practices such as no-tillage and flooding reduce the rate of decomposition of SOM. Understanding the dynamics of SOM with respect to these factors and deriving quantitative relations is important for determining the

trend of SOM under such production systems and for assessing their sustainability. Models can be important research tools to explicitly describe the relations between the various components and to examine the consequences of various intervention measures on changes in SOM and the sustainability of a production system.
Therefore, the research objectives of this study are:

1. Development, calibration, validation and application of a summary model for the quantitative description of the long-term effects of intensive rice-based cropping systems on C and N dynamics of soil.
2. Analysis of the role of SOM in yield formation of rice-based cropping systems and its implications for sustainable food production.

Outline of the thesis

Chapter 2 provides a review of current approaches used in existing SOM models. Furthermore, the processes relevant for describing the long-term dynamics of carbon and nitrogen in rice-based cropping systems of the IGP are discussed.

Datasets collected in long-term experiments in the IGP are evaluated in Chapter 3 by estimating carbon balances for these sites using a simple analytical decomposition model (Yang and Janssen, 2000). A detailed crop model, including the processes of nitrogen limitation developed for rice (LINTUL3), is described in Chapter 4. Chapter 5 describes a summary model, developed for long-term dynamics of carbon and nitrogen in the rice-based cropping systems of the IGP.

Finally, Chapter 6 presents a general discussion with prospects and limitations of the approaches used in modeling and suggestions for future work.

References

Aggarwal, G.C., Sindhu, A.S., Sekhon, N.K., Sandhu, K.S., and Sur, H.S., 1995. Puddling and N mangement effects on crop response in a rice-wheat cropping system. Soil Tillage Research 36, 129-139.

Bandyopadhyay, J., 2001. An Act of Water Acquisition? [Online] http://www.saciwaters.org/literlinking1.htm.

Bhandari, A.L., Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D., and Gupta, R.K., 2002. Yield and soil nutrient changes in a long-term rice-wheat rotation in India. Soil Science Society of America Journal 66, 162-170.

Bhattacharyya, T., Pal, D.K., Chandran, P., Mandal, C., Ray, S.K., Gupta, R.K. and Gajbhiye, K.S., 2004. Managing soil carbon stocks in the Indo-Gangetic Plains, India. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, 44 pp.

Bronson, K.F. and Hobbs, P.R., 1998. The role of soil management in improving yields in the rice wheat systems of South Asia. In: Lal, R. (Ed.) Soil quality and agricultural sustainability. Ann Arbor Press, Chelsea, Michigan, USA, pp. 129-139.

Brown, J.R., 1994. The Sanborn field experiment. In: Leigh, R. A. and Johnson, A. E. (Eds.) Long-term Experiments in Agriculture and Ecological Sciences. CAB International, Wallingford, U.K., pp. 39-51.

Buyanovsky, G.A. and Wagner, G.H., 1998. Changing role of cultivated land in the global carbon cycle. Biology and Fertility of Soils 27, 242-245.

Cassen, R. and Visaria, P., 1999. India: looking ahead to one and a half billion people. BMJ 319, 995-997.

Cassman, K.G. and Pingali, P.L., 1995. Extrapolating trends from long-term experiments to farmer's fields: the case of irrigated rice systems in Asia. In: Barnett, V., Payne, R. and Steiner, R. (Eds.) Agricultural Sustainability in Economic, Environmental and Statistical terms. Wiley, London, pp. 64-84.

Cassman, K.G., Peng, S., Olk, D.C., Ladha, J.K., Reichardt, W., Dobermann, A., and Singh, U., 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. Field Crops Research 56, 7-39.

Dawe, D., Dobermann, A., Moya, P., Abdulrachman, S., Singh, B., Lal, P., Li, S.Y., Lin, B., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., Tan, P.S. and Zhen, Q.X., 2000. How widespread are yield declines in long-term rice experiments in Asia? Field Crops Research 66, 175-193.

DeBusk, W.F. and Reddy, K.R., 1998. Turnover of detrital organic carbon in a nutrient-impacted Everglades marsh. Soil Science Society of America Journal 62, 1460-1468.

Directorate of Agricultural Statistics, 2004. Agricultural Statistics at a glance. New Delhi, India. pp. 220.

Dobermann, A. and Witt, C., 2000. The potential impact of crop intensification on carbon and nitrogen cycling in intensive rice systems. In: Kirk, G. J. D. and Olk, D. C. (Eds.) Carbon and nitrogen dynamics in flooded soils. Proceedings of the workshop on carbon and nitrogen dynamics in flooded soils. IRRI, Makati City, pp. 1-25.

Duxbury, J.M., Abrol, I.P., Gupta, R.K. and Bronson, K.F., 2000. Analysis of long-term soil fertility experiments with rice-wheat rotations in South Asia. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K. (Eds.) Long-term soil fertility experiments with rice-wheat rotations in South Asia, Rice-Wheat Consortium Paper Series 6, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, pp. 7-22.

Gajri, P.R., Arora, V.K., and Prihar, S.S., 1992. Tillage management for efficient water and nitrogen use in wheat following rice. Soil Tillage Research 24, 167-182.

Jenkinson, D.S., 1988. Soil organic matter and its dynamics. In: Wild, A. (Ed.) Russel's soil conditions and plant growth. Longman, New York, USA, pp. 564-607.

Jenny, H. 1980. The soil resource. Origin and behaviour. Springer Verlag, Berlin, 377 pp.

Jenny, H. and Raychaudhury, S.P., 1960. Effect of climate and cultivation on nitrogen and organic matter reserves in Indian soils. Indian Council of Agricultural Research, New Delhi, India, pp. 1-125.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K. and Hobbs, P.R., 2003. How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crops Research 81, 159-180.

Lefroy, R.D.B., Chaitep, W., and Blair, G.J., 1994. Release of sulfur from rice residues under flooded and non- flooded soil conditions. Australian Journal of Agricultural Research 45, 657-667.

Mahapatra, B.S., Sharma, G.L., and Singh, N., 1991. Integrated management of straw and urea nitrogen in lowland rice under a rice wheat rotation. Journal of Agricultural Science 116, 217-220.

Meelu, O.P., Beri, V., Sharma, K.N., Jalota, S.K., and Sandhu, B.S., 1979. Influence of paddy and corn in different rotations on wheat yield, nutrient removal and soil properties. Plant and Soil 51, 51-57.

Nambiar, K.K.M., 1995. Major cropping systems in India. In: Barnett, V., Payne, R., Steiner R. (Eds.), Agricultural sustainability :Economic, Environmental, and statical considerations. Wiley, London, pp. 133-170.

Narang, R.S. and Virmani, S.M., 2001. Rice-wheat cropping systems of the Indo-Gangetic Plains of India. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, and International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradesh, India, 36 pp.

Olk , D.C., Cassman, K.G., 1995. Characterisation of two chemically extracted humic acid fractions in relation to nutrient availability. ACIAR Proceedings No.56.ACIAR, Canberra, Australia, pp. 131-134.

Olk, D.C., Cassman, K.G., Mahieu, N., and Randall, E.W., 1998. Conserved chemical properties of young humic acid fractions in tropical lowland soil under intensive irrigated rice cropping. European Journal of Soil Science 49, 337-349.

Olk, D.C., Cassman, K.G., Randall, E.W., Kinchesh, P., Sanger, L.J., and Anderson, J.M., 1996. Changes in chemical properties of organic matter with intensified rice cropping in tropical lowland soil. European Journal of Soil Science 47, 293-303.

Ortiz-Monasterio, I., Dhillon, S.S., and Fischer, R.A., 1994. Date of sowing effects on grain yield and yield components of irrigated spring wheat cultivars and relationships with radiation and temperature in Ludhiana, India. Field Crops Research 37, 169-184.

Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S.K., Mishra, B., Sastri, A.S.R.A.S., Aggarwal, H.P., Das, D.K. and Gupta, R.K., 2003. Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. Field Crops Research 80, 223-234.

Ponnamperuma, F.N., 1984. Straw as a source of nutrients for wetland rice. In: Banta, S. and Mendoza, C. V., (Eds.). Organic matter and rice. IRRI, Los Banos, Philippines, pp. 117-136.

Prihar, S.S., Ghildyal, B.P., Painuli, D.K., and Sur, H.S., 1985. Physical properties of mineral soils affecting rice-based cropping systems. In: Anonymous (Ed.), Soil physics and rice. IRRI, Los Banos, Philippines, pp. 57-70.

Rai, M., 2002. A perspective for developing action program for sustaining productivity in rice-wheat systems of the Indo-Gangetic Plains. In: Developing an action program for farm level impact in rice-wheat systems of the Indo-Gangetic Plains. Proceedings of the International workshop held on 25-27 September, 2000 at New Delhi, India. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, 131 pp.

Raison, R.J., 1979. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformation: a review. Plant and Soil 51, 73-108.

Ram, N., 1998. Effect of continuous fertilizer use on soil fertility and productivity of a Mollisol. In: Swarup, A., Damodar, R. D. and Prasad, R. N. (Eds.), Long-term soil fertility management through integrated plant nutrient supply. All India Coordinated Research Project (AICRP) on long-term fertilizer experiments, Indian Institute of Soil Science, Bhopal, India, pp. 229-237.

Ram, N., 2000. Long-term effects of fertilizers on rice-wheat-cowpea productivity and soil properties in Mollisols. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K. (Eds.) Long-term soil fertility experiments with rice-wheat rotations in South Asia. Rice-Wheat Consortium Paper Series 6, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 50-55.

Regmi, A.P., Ladha, J.K., Pathak, H., Pasuquin, E., Bueno, C., Dawe, D., Hobbs, P.R., Joshy, D., Maskey, S.L., and Pandey, S.P., 2002. Yield and soil fertility trends in a 20-year rice-rice-wheat experiment in Nepal. Soil Science Society of America Journal 66, 857-867.

Saha, M.N., Saha, A.R., Mandal, B.C. and Ray, P.K., 2000. Effects of long-term jute-rice-wheat cropping system on crop yields and soil fertility. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K. (Eds.) Long-term soil fertility experiments with rice-wheat rotations in South Asia. Rice-Wheat Consortium Paper Series 6, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 94-104.

Scherr, S., 1999. Soil degradation: a threat to developing country food security by 2020? Food, Agriculture and Environment Discussion Paper 27. International Food Policy Research Institute, Washington, D.C.

Sehgal, J.L., Mandal, D.K., Mandal, C., and Vadivelu, S., 1992. Agro-ecological regions of India. Nantional Bureau of Soil Survey and Land Use Planning, Nagpur, India, 130 pp.

Sharma, P.K. and De Datta, S.K., 1996. Physical properties and processes of puddled rice soils. Advances in Soil Science 5, 139-178.

Sidhu, B.S. and Beri, V., 1989. Effect of crop residue management on the yields of different crops and on soil properties. Biological Wastes 27, 15-27.

Singh, B., Singh, Y., and Nayyar, V.K., 2003. Rice-wheat cropping systems in the Indo-Gangetic Plains of India: characteristic features, fertilizer use and nutrient management issues. In: Singh, Y., Singh, B., Nayyar, V. K. and Singh, J. (Eds.), Nutrient management for sustainable rice-wheat cropping system. National Agricultural Technology Project, Indian Council of Agricultural Research, New Delhi and Punjab Agricultural University, Ludhiana, India, pp. 1-17.

Singh, G.B., 1999. Challenges and Opportunities., In: Singh, H. P., Ramakrishna, Y. S., Sharma, K. L. and Venkateswarlu, B. (Eds.), Fifty years of dryland agricultural research in India. Central Research Institute for Dryland Agriculture, Hyderabad, pp. 629-632.

Tripathi, B.P., Ladha, J.K., Timsina, J., and Pascua, S.R., 1997. Nitrogen dynamics and balance in intensified rainfed lowland rice-based cropping systems. Soil Science Society of America Journal 61, 812-821.

Velayutham, M., Mandal, D.K., Mandal, C. and Sehgal, J., 1999. Agro-ecological subregions of India for development and planning. National Bureau of Soil Survey and Land Use Planning, Nagpur, India, 452 pp.

White, J.W. and Rodriguez-Aguilar, A., 2001. An agroclimatological characterization of the Indo-Gangetic Plains. Journal of Crop Production 3, 53-65.

Yadav, R.L. and Subba Rao, A.V.M., 2001. Atlas of cropping systems in India. Project Directorate for Cropping Systems Research, Modipuram, Meerut, India, 96 pp.

Yadav, R.L., Dwivedi, B.S. and Pandey, P.S., 2000. Rice-wheat cropping system: assessment of sustainability under green manuring and chemical fertilizer inputs. Field Crops Research 65, 15-30.

Yadav, R.L., Yadav, D.S., Singh, R.M., and Kumar, A., 1998. Long term effects of inorganic fertilizer inputs on crop productivity in a rice-wheat cropping system. Nutrient Cycling in Agroecosystems 51, 193-200.

Yadvinder, S., Singh, B., Meelu, O.P. and Khind, C.S., 2000. Long-term effects of organic manuring and crop residues on the productivity and sustainability of rice-wheat cropping system in Northwest India. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K. (Eds.), Long-term soil fertility experiments in rice-wheat cropping systems. Rice-Wheat Consortium Paper Series 6, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 149-162.

Yang, H.S. and Janssen, B.H., 2000. A mono-component model of carbon mineralization with a dynamic rate constant. European Journal of Soil Science 51, 517-529.

CHAPTER 2

Quantitative description of soil organic matter dynamics- a review of approaches with reference to rice-based cropping systems*

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Abstract

This review paper presents a historical overview of quantitative approaches used in describing soil organic matter (SOM) dynamics, with the objective of identifying processes relevant in describing long-term carbon and nitrogen dynamics in rice-based cropping systems. A number of existing SOM models have been evaluated based on their objectives and underlying concepts. Models are grouped into two broad classes of analytical and simulation models, and within the latter comprehensive and summary models, based on the level of detail in process descriptions. Most of the existing SOM models have been developed for aerobic, upland conditions and describe the processes of decomposition of organic matter, growth and death of microbial biomass, nitrification, immobilization, denitrification, NH_4^+-volatilization, leaching of NO_3^-, crop uptake, erosion and runoff. However, in anaerobic lowland conditions, the rates and relative importance of the processes are different. This paper evaluates the suitability of existing models for application under alternate flooded and non-flooded conditions, corresponding to rotations of rice-upland crops. Since no existing SOM model describes the processes for such conditions and their effect on SOM quantity and quality, a simulation model is yet to be developed, including these processes, which can satisfactorily describe the changes in SOM and crop yield. This paper also identifies the processes to consider in developing a long-term simulation model for alternate flooded and non-flooded conditions.

Keywords: Soil organic carbon; soil organic nitrogen; model; Indo-Gangetic plains; rice; yield decline

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Introduction

Man has recognized the importance of organic manures for maintaining or improving the fertility of soils since he started farming (Allison, 1973). Recent concepts of sustainable agricultural production to meet the requirements of both farm households and society (Kruseman et al., 1993; Cornelissen, 2003) by reducing the economic and environmental costs of production (Paustian, 1994), also emphasize the importance of soil organic matter (SOM) management for maintaining soil fertility for the future, an absolute condition for sustained production. The potential of agro-ecosystems to absorb large quantities of atmospheric carbon dioxide through carbon sequestration in the form of soil organic matter is widely being put forward as one of the mitigating options for climate change (Lal, 2002; Post et al., 2004). However, soil organic matter content of a given soil type under a particular cropping system with given soil and crop management tends towards an equilibrium value, that is characteristic of the environmental conditions to which that system is exposed (Powlson and Olk, 2000). For example, a legume-based cropping system accumulates carbon at a lower rate than a cereal-based system, as its residues decompose more rapidly, and a soil under continuous flooded rice (rice-rice) accumulates carbon at a higher rate than under a rice-wheat rotation that is aerobic for part of the time. Some agricultural practices such as tillage and puddling accelerate SOM decomposition, whereas others, such as conservation tillage (reduced tillage or no-till), introduction of cover crops, improved crop rotations and balanced fertilizer application enhance build-up of soil organic matter stocks. In recent years, extensive attention has been paid to the sustainability and the effects of crop management practices on resource quality of the rice-based production systems in tropical and subtropical Asia (Cassman and Pingali, 1995; Dawe et al., 2000; Dobermann et al., 2000; Aggarwal et al., 2000). Reports from long-term (LT) experiments under these intensive rice-based systems indicate symptoms of ‘fatigue’, witnessed by stagnating or declining yields (Dawe et al., 2000; Narang and Virmani, 2001; Ladha et al., 2003). One of the many reasons put forward to explain this decline in yield, is the depletion of soil fertility, associated with a reduction in quantity and/or quality of soil organic matter (Ram Nand, 1998; 2000; Dawe et al., 2003). For exploration of the long-term effects of intensive cultivation on soil C and N dynamics, SOM models can be important tools. In such models, the relations between the various components are described explicitly, as well as the influence of environmental conditions, and, following appropriate calibration and validation, they can be used to study soil organic matter dynamics and to explore the possibilities for modification of organic matter content and/or composition through various intervention measures in the system.

Models for understanding and predicting changes in SOM have been developed since the 1940s, ranging from simple exponential decay functions (Henin and Dupuis, 1945) to more complex functions with time-dependent relative decomposition rates in the 1960s (Kortleven, 1963; Kolenbrander, 1969). Following the introduction of simulation modeling techniques in the biological sciences in the 1970s, they were applied also to describe SOM dynamics (Parnas, 1975) and the methodology rapidly expanded (Frissel and van Veen, 1981). A multitude of models has been developed since then, from simple regression equations to complex process-based models, the latter to a large extent retaining the basic principles already incorporated in those early models (van Keulen, 2001). Over the years, several review studies on SOM models have been carried out to establish the state-of-the-art, identify shortcomings in the current modeling approaches and set research priorities for the future. Jenkinson (1990) classified SOM models based on the number of pools as single homogenous, two and multi-component models. Paustian (1994) grouped multi-component models into organism-oriented and process-oriented, based on soil biology and biochemical processes. McGill (1996) grouped 10 process-oriented multi-component models based on relevant attributes, such as their static and dynamic nature, spatial and temporal scale, soil properties and homogeneity of soil horizons, and effect of microbial biomass on dynamics of organic matter. Molina and Smith (1998) reviewed 24 SOMNET[†]-registered models with respect to C and N processes. Smith et al. (1999) reviewed SOM models for tropical ecosystems, covering model use, input requirements, and outputs. Ma and Shaffer (2001) reviewed nine U.S. soil nitrogen dynamics models, as did McGechan and Wu (2001) for European models. They compared the descriptions of soil carbon and nitrogen dynamics in these models and the effect of various environmental factors on these processes. Grace and Merz (2001) classified models based on their main disciplinary orientation into ecological or agro-ecosystem models and agricultural or agronomic models, based on the data used for their calibration.

The objective of this review is to identify relevant processes for the simulation of long-term dynamics of SOM in (flooded) rice-based cropping systems of the Indo-Gangetic Plains (IGP) of India that are characterized by high intensity cultivation, very low soil organic carbon contents (less than 1%) and alternating wet-dry conditions. The review gives a historical overview of quantitative approaches used in describing SOM dynamics and leads to selection of processes relevant to the systems in IGP.

[†] SOMNET. A Global Network and Database of Soil Organic Matter Models and Long-Term Experimental Datasets; www.rothamsted.bbsrc.ac.uk/aen/somnet/.

Soil organic matter: concepts and definitions

Soil organic matter is a mixture of components of different forms and types of biotic origin, and can be broadly classified into living and non-living (Coleman et al., 1989). The living component, which makes up to 4% of the total organic carbon, includes plant roots, macro-organisms and micro-organisms. The non-living biomass, which forms up to 98% of the total organic carbon, can be sub-divided into macro organic matter and humus. Macro-organic matter, commonly referred to as the light fraction, makes up 10-30% of the total organic carbon and consists largely of plant residues in varying stages of decomposition. The dead organic matter, remaining after separation of the light fraction, is called humus. Humus consists of non-humic substances, comprising well-defined classes of organic compounds such as carbohydrates, lipids, and proteins and humic substances, brown- to black-colored compounds formed by secondary synthesis reactions, of relatively high molecular weight. They comprise humic acids (HA), fulvic acids (FA) and humin fractions. These different fractions are not sharply distinguishable in terms of physico-chemical properties and neither in dynamic behaviour. For description of the dynamics of SOM in simulation models, SOM is generally divided into a number of rather arbitrary pools or fractions that are distinguished on the basis of their resistance to microbial action rather than their chemical characteristics.

Terminology: In describing soil organic matter dynamics, various terms are used, such as *carbon turnover, transformation*, *gross decomposition*, *net decomposition, humification* and *mineralization. Carbon turnover* is the general term that includes mineralization and the transformation from one pool to another pool, including microbial biomass. *Transformation* and *gross decomposition* refer to the process in which a substrate is transformed into organic compounds and CO_2, whereas *net decomposition* accounts for the CO_2 component only, either from the original or from the transformed compounds (Yang, 1996; van Keulen, 2001). *Humification* is the process by which carbon of organic residues is converted to humic substances through biochemical and abiotic processes, whereas *mineralization* is the conversion of organic C to CO_2 and is therefore similar to *net decomposition*. Rate equations for transformation of various soil organic matter pools are described by *zero-order*, *first-order*, or *Michaelis-Menten* (Monod) kinetics. A zero-order process proceeds at a constant rate, independent of the substrate (C) concentration ($dC/dt = -k_0$), while the rate of a first order reaction is proportional to the substrate concentration ($dC/dt = -k_1 C$). In Monod-type kinetics, the reactions are described as biological processes with rates depending on the amount of microbial biomass which is involved in the utilization of a substrate ($dC/dt = -(dC/dt)_{(max)} C/ (K_c + C)$). In these equations, k_0 is the rate constant for a zero order reaction, k_1 is the relative rate constant for a first order reaction, and K_c represents the half-saturation concentration, where the rate is equal to half of the maximum $((dC/dt)_{(max)})$, defined as a function of microbial biomass.

A historical overview of quantitative descriptions of SOM

Soil fertility is linked to SOM status through its influence on soil physical properties and plant nutrient supply. Results from many short- and long-term experimental studies conducted in the laboratory as well as under field conditions since the 1940s (Henin and Dupuis, 1945; Springer and Lehner, 1952; Kortleven, 1963; Sauerbeck and Gonzalez, 1977) were used for providing guidelines for farmers about crop and soil management. For that purpose, simple regression models, based on exponential decay, appeared successful. From the mid-1970s, improved computing facilities and better understanding of the processes led to rapid development of dynamic SOM models, as illustrated in 1980, in a workshop on the state of the art of modeling of soil nitrogen processes (Frissel and van Veen, 1981). Progress in the subsequent years is illustrated in the proceedings of a workshop organized by NATO in 1995, for the evaluation of SOM models using long-term datasets (Powlson et al., 1996). In this section, existing SOM models are briefly discussed, based on their objectives and theoretical basis and classified on the basis of the type of quantitative description. We distinguish analytical models and simulation models, and within the latter group, comprehensive and summary models.

Analytical models: The models described in this section mostly consider SOM as a single homogenous pool that decomposes with varying relative rates of decomposition.

Henin-Dupuis (1945)

Among the first to quantitatively describe SOM dynamics in soil were Henin and Dupuis (1945). They assumed that fresh organic material added to the soil would decline in an exponential way according to:

$$dY/dt = -kY \tag{1}$$

Solving Eqn. (1) analytically results in:

$$Y = Y_0 e^{-k t} \tag{2}$$

where Y is the content of SOM (g kg^{-1}) at time t; Y_0 is the content of SOM (g kg^{-1}) at t = 0; k = relative decomposition rate ($year^{-1}$).

Kortleven (1963)

Kortleven adopted the concept of Henin and Dupuis (1945), and in addition assumed that this conversion of fresh organic matter into humus can be represented by two constants: h, the fraction of organic material remaining in the soil after one year (i.e. the humus fraction or humification coefficient) and k, the relative decomposition rate of the humus. Both h and k appeared dependent on the type of organic material used.

Kolenbrander (1969)

Kolenbrander returned to the Henin-Dupuis (1945) approach with total organic matter considered as a single pool, however, with a relative decomposition rate decreasing with time. He described the dynamics of (residual) organic matter as:

$$Y_t = Y_0\, e^{-(n+p/(t+1))\,t} \tag{3}$$

where k, averaged over the time period 0 to t, can be estimated from: $k_{0\text{-}t} = n+p/(t+1)$. In this equation, n (dimension t^{-1}) and p (dimensionless) are empirical constants, with values specific for a given type of organic material. Average $k_{0\text{-}t}$ decreases with time, and equals n when $t=\infty$.

Sauerbeck and Gonzalez (1977)

Sauerbeck and Gonzalez (1977) conducted long-term decomposition experiments with ^{14}C-labelled plant material in soils of temperate and tropical origin, varying in carbon content, to determine the equilibrium concentration and organic matter requirements for soil humus maintenance. During the first year, 65% of the added material disappeared and stable residues and turnover products followed an exponentially decreasing function. These results suggest the existence of two independent organic fractions: an easily decomposable labile fraction, and a more resistant stable fraction. Decomposition curves of the more stable compounds and turnover products followed a first–order reaction, with k decreasing with time, comparable to n+p/(t+1).

Janssen (1984)

Combining the two-fraction approach (labile and stable organic matter) of Sauerbeck and Gonzalez (1977) and the Kolenbrander approach (1969), Janssen proposed an equation in which the relative rate of decomposition (k) is defined as an empirical function of the 'initial age' (*a*) of the organic material:

$$k = 2.82\ (a + t)^{-1.6} \tag{4}$$

Integration of dY/dt = – kY, with k from Eqn. 4 leads to Eqn. 5, that can be used to (iteratively) derive the value of *a* for specific organic materials from Y_0 and at least one value of Y_t:

$$Y_t = Y_0\ e^{(4.7\ [(a+t)^{-0.6} - a^{-0.6}])} \tag{5}$$

$$h = Y_1/Y_0 = e^{(4.7\ [(a+1)^{-0.6} - a^{-0.6}])} \tag{6}$$

with Y_1 the residual organic matter after one year.

Yang (1996)

Yang, starting from Janssen's model, introduced K, the average k between time 0 and t, and found a linear relationship between ln(K) and ln(t) for a range of experiments, covering incubation experiments as well as field trials and for substrates ranging from glucose to plant materials, peat and SOM:

$$\ln(K) = \ln(R) - S\ \ln(t) \text{ or}$$
$$K = R\ t^{-S} \tag{7}$$

In which R and S are regression constants, with R = K when t = 1. Hence, R represents the average relative decomposition rate for t = 0 to 1, $k_{0\text{-}1}$. The slope of the regression line represents the rate at which K decreases over time that is equivalent to the rate of 'ageing' (Janssen, 1984) of the substrate.

Substitution of K in the equation $Y_t = Y_0\ e^{-kt}$ yields:

$$Y_t = Y_0 e^{(-R\ t^{1-S})} \tag{8}$$

To account for the effect of temperature on organic matter decomposition (Janssen, 1986; Noij et al., 1993; Raijmakers and Janssen, 1995), Eqn. 8 was modified to:

$$Y_t = Y_0 e^{(-R\ (ft)^{1-S})} \tag{9}$$

The correction factor *f* allows translation of the value of R obtained at a specific temperature into values at other temperatures.

SOMM (Soil Organic Matter Mineralization)

The SOMM model (Chertov and Komarov, 1997, 1996) was developed as a tool for theoretical analysis of natural ecosystems and simulates soil organic matter mineralization, humification and nitrogen release. The experimental basis for SOMM was a set of laboratory experiments on organic matter decomposition in the presence of a complex of microorganisms (fungi, actinomycetes, and bacteria) and micro fauna (arthropods, earthworms, etc). The model consists of a system of linear differential equations with variable coefficients:

$$dL/dt = L_0 - (k_1+k_3)\, L$$
$$dF/dt = k_3L - (k_2+k_4+k_5)\, F$$
$$dH/dt = (k_4+k_5)\, F\, M_f - k_6H$$

where L_0 is the litter input rate, L the non-decomposed part of the litter remaining in the soil, F the complex humic substance (CHS) with non-decomposed plant debris, and H the humus content. k_1 and k_2 are the relative rates of C losses from L(itter) and from F(complex humic substance). k_3, k_4, k_5 and k_6 are the relative decomposition rates for litter transformation to CHS, CHS consumption by micro-organisms, CHS consumption by earthworms, and humus mineralization, respectively. M_f is the fraction of CHS transforming to humus. The relative rates of decomposition are modified for soil temperature and moisture content and for nitrogen and ash content of litter.

ICBM (Introductory Carbon Balance Model)

The ICBM model (Andrén and Kätterer, 1997) has been developed for long-term predictions of carbon dynamics in soil to estimate its carbon sequestration capacity. The differential equations in this two-compartment model comprising Young (Y) and Old (O) organic matter pools are solved analytically. The effect of climatic factors is condensed into a single parameter (r) that similarly affects the decomposition rates of young and old organic matter:

$$dY/dt = i - k_1\, Y\, r$$
$$dO/dt = h\, k_1 Y\, r - O\, k_2\, r$$

where *i* is mean annual C input into the soil, defined as a parameter that needs to be optimized for a particular ecosystem based on experiments or available literature; k_1 and k_2 are relative decomposition rates for young and old organic matter, respectively and h is the humification coefficient, i.e. the fraction of young organic matter that is transferred annually to the old. The value of h is defined in dependence of litter quality and external factors such as soil type.

Simulation models: Application of a process-based modeling approach to simulate SOM dynamics was initiated by Parnas in 1975. The models described in this section consider SOM as heterogeneous mixtures, and decomposition of components in this mixture, represented by a number of arbitrary pools, takes place at different relative rates. Models described in this section are divided into two groups: comprehensive and summary models. A comprehensive model, generally designed for research purposes, is a model of a system whose essential elements are thoroughly understood, and in which the available knowledge is incorporated (Penning de Vries, 1982). In summary models, more suitable for applicative and predictive purposes (van Ittersum et al., 2002), essential aspects of comprehensive models are formulated in less detail.

Comprehensive models

PAPRAN (Production of Annual Pasture limited by Rainfall And Nitrogen)

The PAPRAN model developed by Seligman and van Keulen (1981) distinguishes two fractions of soil organic matter: fresh, which is defined in terms of its components, simple sugars, cellulose/hemicellulose and lignin, and stable. Microbial biomass is considered as part of the fresh organic material, assuming micro-organisms are not rate-limiting for decomposition. The decomposition rate of organic material is based on first-order kinetics and depends on soil temperature, soil moisture and C: N ratio of the substrate. Since decomposition of fresh organic matter depends on its composition, the relative rate of decomposition declines sequentially with increasing C/N ratio as more easily decomposable fractions vanish.

Juma and Paul (1981)

This model was developed to test the concepts of soil microbial growth and decay and to study mineralization and immobilization of soil N under laboratory conditions. Soil organic matter is represented by active, stabilized and old pools. The active pool is further sub-divided into biomass, active and metabolites. Similarly, the passive pool is sub-divided into a stabilized component with a half life of around 35 years and an old pool with a half life of around 600 years, equivalent to time constants of 50 and 865 years, respectively. The dynamics of microbial growth and N immobilization are described by first-order kinetics. On decomposition of carbon substrates, a portion of the carbon is transferred to the microbial biomass pool and the remaining part is released as CO_2. Microbial biomass also undergoes decomposition and on decay, 50% of the products is channeled to the active pool and the remainder to the metabolite pool. The active and metabolite pools also undergo decomposition and are transformed into biomass, while CO_2 is released. Part of the active carbon that is transferred to the stable pool is subsequently transferred to the old pool. The rate of N mineralization follows from decomposition of the carbon components by dividing by the C/N ratio of the pools.

van Veen and Frissel (1981)

This model also emphasizes the role of microorganisms, and organic matter dynamics are controlled by growth and activity of the soil microbial biomass. It is a multi-layer, multi-component model, with varying numbers of soil layers and six organic carbon pools (Table 2). Decomposition rate of soil organic matter is controlled by the uptake of carbon by the growing microbial biomass. The rate of carbon release from the decomposable pools (1-4) used for biosynthesis and maintenance of microbial biomass is described by Monod-type equations and the rate of loss of carbon from the resistant and the old organic matter pools (5 and 6) is described by first-order kinetics. Nitrogen in the decomposing organic matter in excess of what is needed for biomass synthesis is transferred to the mineral nitrogen pool, the quantity depending on the C/N ratio of substrate and biomass. N-immobilization is proportional to the growth rate of biomass (in carbon equivalents) and is calculated by dividing the growth rate of the biomass by its C/N ratio.

NCSOIL (Nitrogen and Carbon Transformation in Soil)

NCSOIL (Molina et al., 1983) is a module of a larger model describing C and N flows in the soil-water-air-plant system (NCSWAP). Soil organic matter is sub-divided into fresh plant residues, microbial biomass, a labile and a stable organic pool. Decomposition of the pools proceeds independently with relative rates that fall below the potential when not enough nitrogen is available to satisfy the demand of the growing microbial biomass. The reduction factor equals the ratio of total N available and that required for potential growth. The model provides the choice to select first-order or Monod-type kinetics for residue decomposition.

ANIMO (Agricultural Nutrient Model)

ANIMO (Rijtema and Kroes, 1991) quantifies the relations between fertilizer dose, soil management and leaching of nutrients to ground- and surface water systems for a wide range of soil types and hydrological conditions. It simulates the carbon, nitrogen and phosphorus cycles in unsaturated and saturated soil systems. In the model, a fixed number of possible materials: fresh organic matter, dissolved organic matter, root exudates, and humus consisting of a fixed number of pools or classes (Table 2) has to be defined by the model user. With appropriate parameter sets for different classes and first-order rate constants for a given organic material, ANIMO is able to reproduce results of the empirical equations of Kolenbrander (1969) and Janssen (1986). The model performs well also for nature and forest areas (Kroes and Roelsma, 1998) and has been used for both field and regional applications.

Ecosys (Ecosystem model)

Ecosys (Grant et al., 1993; Grant and Rochette, 1994; Grant, 2001; Grant et al., 2001) has been developed for natural and managed ecosystems with the objective that model parameters should have a physical or biological meaning and that the model can be applied to different spatial and temporal scales. Ecosys simulates processes of soil water, heat, carbon, oxygen, nitrogen, phosphorus including ionic (Al^{3+}, Fe^{2+}, Ca^{2+}, etc.) transport and gaseous (CO_2, methane and N_2O) exchanges with a range of management options, including tillage and residue management. Microbial biomass is an active agent of organic matter transformation in the model. Soil organic matter is divided into four substrate-microbe complexes: plant residue, animal manure, particulate (active), and non-particulate (passive) organic matter in five different states: solid, solubilized, adsorbed, microbial and microbial residue. Each organic state in each complex is further divided into carbohydrate, cellulose, and lignin with varying rates of relative decomposition. Microbial communities are further grouped into obligate aerobic and anaerobic, facultative anaerobic and methanogens. Rates of decomposition of each substrate-microbe complex depend on the substrate-microbe density relationships, temperature and water content. Residue decomposition products undergo humification at a rate that depends on that of residue decomposition and soil clay content. A fraction of lignin coupled with protein and carbohydrate is transferred to the solid substrate of active SOM. Products of microbial decomposition are partitioned between microbial residues within the same substrate-microbe complex, and the solid substrate of the passive SOM complex depends on soil clay content (Grant et al., 2001).

DNDC (DeNitrification DeComposition)

This model (Li et al., 1994) was developed for estimating the effects of climate change, land use, agricultural management, soil properties, and atmospheric nitrogen deposition on soil C and N dynamics in forested upland and wetland ecosystems (Wetland-DNDC). DNDC consists of four submodels of soil conditions, decomposition, denitrification, and plant growth. The structure of the SOM pools in the decomposition submodel was adopted from NCSOIL (Molina et al., 1983). The SOM pools consist of several sub-pools (Table 2), each with its own C/N ratio and relative rate of decomposition. The decomposition sub-model calculates daily decomposition, carbon dioxide production, nitrification, and ammonia volatilization. The denitrification sub-model calculates the denitrification rate, nitrous oxide (N_2O) and dinitrogen (N_2) production in the soil. Effects of cropping practices, including tillage, fertilizer and manure application and irrigation are accounted for. The wetland-DNDC model is an extension from the original DNDC for upland conditions, and quantifies vertical and lateral water flows, and simulates the soil redox potential (Eh) and its effect on soil carbon and nitrogen processes. The redox potential governs the microbial oxidation-reduction processes, including production and consumption of CO_2, methane (CH_4), nitrous oxide (N_2O) and nitric oxide (NO). DNDC has been used for studies on alternative agricultural practices, to estimate soil carbon sequestration and regional trace gas emissions (Li et al., 1995) and to explore possibilities for mitigating greenhouse gas emissions (Li, 1995).

NICCCE (Nitrogen Isotopes and Carbon Cycling in Coniferous Ecosystems)

NICCCE (van Dam and van Breemen, 1995) was developed to simulate heat and water flows and nitrogen and carbon cycling in coniferous forests. The model is used to interpret the results of experiments on atmospheric nitrogen input into coniferous forest ecosystems in Europe. Rates of processes in NICCCE are described by one of three types of kinetics: zero-order, first-order, and Michaelis-Menten. Litter from trees, consisting of carbohydrates, proteins, hemicellulose, and lignin is used as substrate by microbes and is decomposed according to first-order kinetics. The resulting microbial litter, consisting of both necromass and dissimilation products, is partitioned into metabolic and structural pools. The metabolic pool, with low C/N ratio, is easily decomposable, whereas the structural part is less easily decomposable because of a high C/N ratio. Microbial litter decomposes according to Michaelis-Menten kinetics for the metabolic pool and first-order for the structural pool. Part of the structural pool is transferred to the humic pool, subsequently to a stable pool and finally to a resistant pool. The turnover time of the soil organic matter pools is modified for soil texture, temperature and moisture effects.

EPIC (Erosion Productivity Impact Calculator)

The carbon and nitrogen processes in EPIC (Williams, 1995) are modifications of the PAPRAN model (Seligman and van Keulen, 1981). Three functional pools of soil organic matter are distinguished: fresh organic carbon, active soil humus, and stable humus. The stable humus pool is not mineralizing at all (Ma and Shaffer, 2001). For the active pool, the fraction RTN is calculated as $0.4\ e^{(-0.0277\ YC)} + 0.1$, where YC is number of years in cultivation. N mineralization is described as a first order process with a mineralization rate depending on soil water content, temperature, C/N and C/P ratio. About 20% of the nitrogen mineralized goes to the active humus pool and 80% to the mineral N pool. The model has been recently modified using concepts of CENTURY to simulate soil carbon dynamics as affected by soil erosion and tillage (Izaurralde et al., 2001).

APSIM (Agricultural Production Systems Simulator)

APSIM (McCown et al., 1996; Keating et al., 2003) is a modeling framework consisting of plant, soil and management modules for a diverse range of crops, pastures and trees, soil processes and management situations. Soil organic matter processes in the model are described with two modules: SoilN and Residue. The SoilN module simulates mineralization of N from soil organic matter and crop residues. In the SoilN module, SOM is divided into a fresh organic matter pool (FOM), a labile (BIOM) and a stable (HUM) pool. The flows between different pools are calculated in terms of carbon, and the corresponding N flows depend on the C/N ratios. The Residue module describes the effect of crop residues on the soil surface on the soil water balance. Crop residues, added to the surface residue pool are characterized in terms of mass, nitrogen content and the cover they provide. Three types of residue management are considered, viz. removal, incorporation and in situ decomposition. In the latest versions of APSIM (http://www.apsim.info/apsim/Apsim/Docs/shared/Release%20notes.htm), a new module (SurfaceOM) has replaced the previous Residue and Manure modules. This module enables to specify, if necessary, different C/N and C/P ratios for each of the fresh organic matter pools (carbohydrate, cellulose, and lignin).

RZWQM (Root Zone Water Quality Model)

RZWQM (Ahuja et al., 1999; Ma et al., 2001) is an agricultural system model, simulating agricultural production and environmental quality. A nutrient module, OMNI, simulates carbon and nitrogen transformations in the soil profile. The model distinguishes five organic C and N pools: two residue pools and three soil organic matter pools (Table 2). First order decomposition kinetics are used for all pools and the first order rate coefficients are modified for the effects of soil temperature, oxygen, hydrogen, degree of aeration, aerobic heterotrophs and ionic strength. A fraction of the organic C from decomposing organic matter is assimilated into microbial biomass. Net assimilation is calculated from the C/N ratio of the microbial biomass and those of the respective pools. Total growth of aerobic heterotrophs is the sum of growth via the five organic pools. The autotrophs simulated in the model acquire their energy from nitrification and it is assumed that a fraction of the total nitrified NH_4^+-N is assimilated into microbial biomass. Nitrification is simulated as a zero order process with a nitrification rate that is affected by soil temperature, oxygen concentration, soil pH, and population density of the autotrophs. The facultative heterotrophs grow in association with the denitrification process, using an efficiency factor to partition a fraction of the denitrified NO_3^--N to growth of microbial biomass. Denitrification is described as a first order process, with a relative rate defined as a function of soil anaerobic conditions, soil temperature, soil pH, soil carbon substrate, and population density of the denitrifiers.

Summary models

Osnabruck model

The Osnabruck model (Esser, 1987; 1991; Lieth, 1975) was used to model changes in global Net Primary Production (NPP) and C fluxes associated with historical land use patterns. The basic spatial resolution is a 2.5 × 2.5° grid cell and the model operates with an annual time step. The model distinguishes herbaceous and woody litter pools and a lignin pool. Specific decomposition rates are modified by the minimum of either the temperature or precipitation limitation.

RothC (Rothamsted Carbon Model)

RothC (Coleman and Jenkinson, 1996) is a transformation model that simulates the turnover of organic carbon in non-waterlogged soils in monthly time intervals and allows for the effects of soil type, temperature, moisture content and plant cover. It is an extension of earlier models described by Jenkinson and Rayner (1977) and Hart (1984). Soil organic matter is divided into five components (Table 2) with different decomposition rates. Total organic carbon, microbial biomass carbon and $\Delta^{14}C$ (from which the equivalent radiocarbon age of soil organic matter can be calculated) are calculated on a time scale from years to centuries (Jenkinson *et al.* 1987; Jenkinson, 1990; Jenkinson *et al.* 1991; Jenkinson *et al.* 1992; Jenkinson and Coleman, 1994). The effects of temperature, soil moisture and soil cover on decomposition are included through correction factors. Many concepts in RothC are similar to those in van Veen and Paul's model (1981) and the CENTURY model (Parton et al., 1988).

CENTURY

CENTURY (Parton et al., 1987; Parton et al., 1988; Parton and Rasmussen, 1994) was developed as a SOM model to which later a crop growth module has been added. The model simulates the dynamics of carbon, nitrogen, phosphorus, and sulfur for different plant production systems such as grassland, arable land, forests, and savannas (minimum 10 years) with a monthly time step[‡]. The SOM sub-model is similar to some other multi-component models (Jenkinson and Rayner, 1977; van Veen and Paul, 1981; Jenkinson, 1990). The model partitions plant residues among structural and metabolic organic pools, based on their lignin/N ratio. The structural pool is further sub-divided into lignin and cellulose components. Metabolic and cellulose C are transferred to the active pool (i.e. microbial biomass), whereas lignin C is transferred directly to the slow pool. Decomposition of all pools is described according to first-order kinetics with different relative rate constants per pool that vary for different systems like arable crops, grass and forest (Table 2). The actual relative rate of decomposition for the structural pool is derived from its lignin content, whereas for the active pool it is modified for soil texture, in addition to the modifications for soil temperature and moisture content. Nitrification is not incorporated, as in the mineral soil nitrogen pool no distinction is made between ammonium and nitrate.

Verberne

This model (Verberne et al., 1990) is based on the models of van Veen (van Veen and Paul, 1981) and describes carbon and nitrogen cycling in different soil types, with the objective of predicting the daily net rate of mineralization. The model divides organic material into 3 pools of residues and 4 pools of soil organic matter (Table 2) based on biochemical composition, C/N ratio and lignin content. The model considers the effect of 'soil protection' on SOM, which depends on soil type (clay and silt content) and cultivation method. All transformations between pools are described by first-order kinetics. Each transformation is characterized by a decomposition rate constant (k) and a yield efficiency factor (E), expressing the fraction of carbon from the decomposing material incorporated into microbial biomass, the remainder being lost as CO_2. Sub-optimal conditions of temperature, soil moisture content, and soil pH are taken into account through modification factors with values between 0 and 1.

DAISY

DAISY (Hansen et al., 1990; Mueller et al., 1996) is a crop growth model incorporating soil water and heat flows, and carbon and nitrogen dynamics, developed for the wet temperate climate of N-W Europe. Transformations between the different pools distinguished in the SOM sub-model of DAISY (Table 2) are based on first-order kinetics. Sub-pools of biomass are characterized by a substrate utilization efficiency, a maintenance respiration coefficient and a death rate coefficient. During biomass growth and decay, carbon is partly lost as CO_2, and the remainder is

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[‡] A modified version, called DAYCENT simulates at a daily time step.

partitioned among various sub-pools of organic matter. Rates of transformation are modified in dependence of soil temperature, water and clay content.

SUNDIAL

SUNDIAL (Bradbury et al., 1993; Smith et al., 1996) is based on RothC, but extended to include N turnover. Decomposition is represented by flows between three pools (Table 2), represented by first-order kinetics, with specific rate constants for each pool. Of each flow, a fraction α is converted into microbial BIOmass, a fraction β is converted into HUMus and the remainder is lost as CO_2. These rate constants are modified as function of soil temperature and water content. The effect of soil texture on decomposition is accounted for by adjusting the fractions α and β as a function of soil clay content.

CANDY (Carbon and Nitrogen Dynamics)

CANDY (Franko et al., 1995; Franko, 1996) was developed with the objective to give farmers a tool to calculate short-term dynamics of nitrogen transformations and long-term changes in soil carbon content. The model allows specification of up to six categories of fresh organic matter, including manure and/or slurry. It distinguishes three sets of pools: fresh organic matter (FOM), biologically active organic matter (BOM), and slow-cycling soil organic matter (SOM). Carbon moves out of each pool according to first-order kinetics, with rate constants adjusted for the effect of environmental factors, such as temperature, soil water content and soil aeration. A synthesis coefficient, η, represents the proportion of carbon from FOM transferred to the BOM pool, the remainder being released as CO_2. Nitrogen mineralization and immobilization are derived from the carbon transfers between pools, taking into account the specific C/N ratio of each pool.

SOCRATES

SOCRATES (Grace and Ladd, 1995) was developed to estimate changes in soil organic carbon (SOC) as influenced by cropping pattern, including pastures. The main consideration in its development was that the input data could be easily measured in the laboratory. Soil organic matter is partitioned in five components (Table 2), with partitioning of plant materials into decomposable and resistant fractions based on their N content. At initialization, 2% of the measured SOC is assumed protected and the remaining 98% defined as stable humus. Carbon flows to the microbial biomass, humus and CO_2 and the relative decomposition rates for each of the components were calibrated using ^{14}C data of Ladd et al. (1995). The effect of temperature on decomposition is described by a Q_{10} of 2. Reduction factors to account for water shortage are calculated on the basis of a detailed water balance, using the ratio of actual to potential evapo-transpiration.

Evaluation of SOM models

In the description of SOM dynamics, two approaches can be distinguished from the point of view of SOM characterization: In the first approach, the organic matter pool is considered as a single entity with a characteristic relative decomposition rate (k), that is either constant or changes with time (Henin and Dupuis, 1945; Kortleven, 1963; Kolenbrander, 1969; Janssen, 1984; Yang, 1996; Table 1). In the second approach, soil organic matter is divided into a number of functional pools, that varies from two (Seligman and van Keulen, 1981; van Veen and Frissel, 1981) via three (Parton et al., 1987) to as many as seven (Juma and Paul, 1981).

In the first approach, the variation in k values of the different organic materials is associated with their different chemical composition in terms of sugars, proteins, cellulose and lignin. In Eqn. (3) that describes organic matter decomposition with a time-dependent relative decomposition rate, i.e. $n+p/(t+1)$, the relative decomposition rate refers to the total period from the starting time ($t = 0$) till time t and is denoted as k_i. Differentiation of Eqn. (3) yields: $dY/dt = -(n + p / (t + 1)^2) Y$, i.e. a time-dependent relative decomposition rate of $(n + p / (t + 1)^2)$, the momentary value, denoted as k_m. This concept of an integrated and a momentary k, is comparable to Eqn. (4) of Janssen with $k_i = 4.7 [(a + t)^{-0.6} - a^{-0.6}]$ and $k_m = 2.82 (a + t)^{-1.6}$; and Eqn. (7) of Yang with $k_i = R t^{-s}$ and $k_m = (1-S) R t^{-s}$ Eqns. (3) and (4) yield comparable results (Figure 1). Such a time-dependent decreasing relative decomposition rate reflects the chemical composition of the substrate with a higher k at the start, corresponding to decomposition of the more easily decomposable parts, and a lower k later, corresponding to decomposition of the more resistant parts of SOM. For Yang's model, where the rate of decomposition also depends on temperature, the turnover time of SOM could be expressed in *physiological time*, i.e. a cumulative temperature sum required to reach equilibrium with soil humus. Analytical models with such simple equations are easy to use, and in many studies (Janssen, 1984; Yang, 1996; Kätterer et al., 2004) such models were able to quantify the changes in SOM under different environmental conditions. The major limitation of analytical models is that they do not allow inclusion of effects of various crop and soil management practices on SOM dynamics.

In the second approach, both, the existing and the added materials are partitioned into a number of pools each with its own specific rate constant. Most of the current multi-

Table 1. Rate equation, Parameters and integral form of mono-component analytical models.

Model	**Rate equation**	**Parameters**	**Integral form**
Henin-Dupuis	kY	k	$Y_0\ e^{-kt}$
Kortleven	kY	h, k $(h = Y_1/Y_0)$	$Y_0\ e^{-kt}$
Kolenbrander	KY	n, p, K $(K = n+p/(t+1))$	$Y_0\ e^{-(n+p/(t+1))\ t}$
Janssen	kY	a, k $(k = 2.82\ (a+t)^{-1.6})$	$Y_0\ e^{(4.7\ [(a+t)^{-0.6} - a^{-0.6}])}$
Yang	KY	R, S, f, K $(K = R\ f\ (f\ t)^{-S})$	$Y_0\ e^{(-R\ (f\ t)^{1-S})}$

Y= soil organic matter at time t, Y_0= initial soil organic matter, k= relative decomposition rate, K= Average relative decomposition rate (k_{0-t}), h= humification constant, a= ageing factor, f = temperature correction factor.
n, p, R, and S are regression constants.

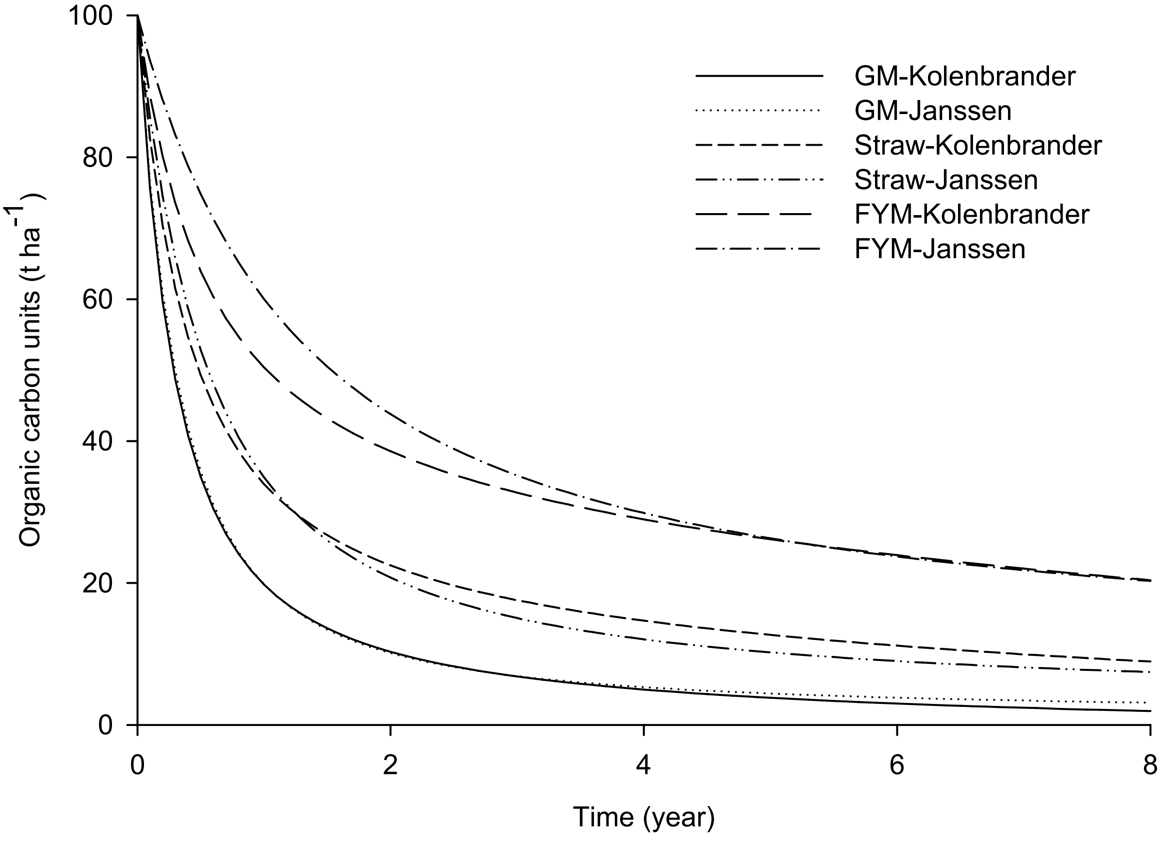

Figure 1. Comparing the analytical models of Kolenbrander (Eqn. 3) and Janssen (Eqn. 5) for various organic materials such as green matter (GM), straw and farmyard manure (FYM).

Table 2. Characteristics of some multi-compartment SOM models for comparison (*See text for literature references to the models*).

Model	C pools[*]	C/N ratio	Residence time (y)	Type[**]	Soil compartments	Temporal scale	Spatial scale	Scope
PAPRAN	Fresh	Variable	0.03-2.88	C	10	Seasonal	Plot and field scale	Annual pasture or a small-grain crop growing in a homogenous soil in a semi-arid environment
	Stable	10	33.0					
Van Veen and Frissel	Plant residue (pool 1)		0.014	C	Variable depends on the situation	Seasonal		Intensive agricultural systems of N-W Europe, characterized by temperate climate and high N dressings
	Plant residue (pool 2)		0.034					
	N-containing SOM (pool 3)		0.274					
	Microbial residues (pool4)		0.009					
	Resistant active C (pool 5)		0.548					
	Recalcitrant old C (pool 6)		342					
Juma and Paul	Biomass	6	0.19	C		Short term	Laboratory experiments	Laboratory experiments
	Active	6	0.74					
	Metabolite	3	0.003					
	Old	11.8	913.0					
	Stable	11	4.5					

Table 2. Continued.

Model	C pools[*]	C/N ratio	Residence time (y)	Type[**]	Soil compartments	Temporal scale	Spatial scale	Scope
ANIMO	Slurry fraction 1	8.3	0.03	C	User defined (20 or more)	Short term	Plot, field, catchments, regional, and national	Arable, wetland and grassland ecosystems
	Slurry fraction 2	11.6	1.01					
	Slurry fraction 3	58	8.30					
	Crop residues (fast)	58	0.50					
	Crop residues (slow)	39	4.57					
	Root exudates	23	0.003					
Verberne	DPM	6.0	0.014	S	Compartments of 5-cm depth	Short and long term	Plot, field	Grazed and arable ecosystems
	SPM	150	0.027					
	RPM	100	0.137					
	BIOM	8.0	0.005					
	AOM (POM and NOM)	10-15						
	SOM	10-20	3425.0					
NICCCE	Microbial biomass (metabolic)	C/N ratio obtained by fitting		C	Depends on profile morphology	Long term	Plot, field, catchments	Closed canopy forests (more than 20 years), used to predict ecosystem response to various climate change scenarios for environmental policy purposes.
	Microbial biomass (structural)	C/N ratio obtained by fitting						
	Humic		10-20					
	Stable		50-100					
	Resistant		500-2000					

Table 2. Continued.

Model	C pools[*]	C/N ratio	Residence time (y)	Type[**]	Soil compartments	Temporal scale	Spatial scale	Scope
DAISY	AOM 1	100	0.06	S	5	Short term and Long term	Plot, field, catchments	Arable ecosystem in cool temperate climate
	AOM 2	-	0.04					
	SMB 1	6	0.28					
	SMB 2	10	2.78					
	SOM 1	12	1000					
	SOM 2	10	20.0					
SUNDIAL	RO	5-70	0.12	S	12	Short term	Plot, field	Arable ecosystem in cool temperate climate
	BIO	8.5	1.5					
	HUM	8.5	48.0					
RothC	DPM	half of the plant material is DPM	0.1	S	1	Short and long term	Plot, field, catchments, Regional, national, and global	Natural vegetation, grazed ecosystem, arable ecosystem and forest ecosystem.
	BIO	half of the BIO+HUM	1.5					
	RPM	half of the plant material is RPM	3.3					
	HUM	half of BIO+HUM	50.0					
	IOM	-	50000					
	Roots	25						
	Litter (plant residues and roots)	60	0.078					
	Faeces	50	0.078					

Table 2. Continued.

Model	C pools*	C/N ratio	Residence time (y)	Type**	Soil compartments	Temporal scale	Spatial scale	Scope
CANDY	FOM	variable	2.5	S	20	Short and long term	Plot, field, and catchments	Arable ecosystem in a cool temperate climate
	BOM	8.5	7.14					
	SOM	8.5	20.0					
ICBM	Young	Pool estimation based on observed data/literature	1.25	A	1	Medium term (30 years)	Microsite to regional and global level	Arable ecosystem in cool temperate climate
	Old		166					
NCSOIL	Residue pool			C	1	Short term	Plot and field scale	Natural vegetation and arable ecosystem
	Pool I labile	6	0.01					
	Pool I resistant	6	0.07					
	Pool II labile	6	0.45					
	Pool II resistant	6	1.72					
	Pool III (stable humus)	12	25.0					
CENTURY	Structural	150	1-5	S	1	Long term	Plot, field, regional, national, and global	Natural vegetation, grazed ecosystem, arable ecosystem, and forest ecosystem
	Metabolic	10-30	0.1-1					
	Active SOM	3-14	1-5					
	Slow SOM	12-20	20-40					
	Passive SOM	11-12	400-2000					
EPIC	Fresh pool		-	C	Up to 10		Field	Arable ecosystems
	Active pool	12-25						
	Stable pool	<12	33					

Table 2. Continued.

Model	C pools[*]	C/N ratio	Residence time (y)	Type[**]	Soil compartments	Temporal scale	Spatial scale	Scope
DNDC	Very labile litter	2.35	0.04	C	10	Short and long term	Plot, field, and regional	Arable and wetland ecosystems
	Labile litter	20	0.04					
	Resistant litter	20	0.14					
	Labile microbial biomass	8	0.01					
	Resistant microbial mass	8	0.07					
	Labile humads	8	0.02					
	Resistant humads	8	0.45					
	Passive humus							
APSIM	Fresh OM	Variable	0.01-0.29	C	User defined	Short term	Plot to field level	Arable ecosystems, forest ecosystems
	BIOM	8.0	0.34					
	HUM	Derived from the C/N ratio of soil	18.26					
SOCRATES	DPM		0.02	S	1		Plot	Grazed and arable ecosystem
	RPM		0.32					
	Unprotected MB		0.003					
	Protected MB		0.35					
	Stable OM		21.31					

Table 2. Continued.

Model	C pools*	C/N ratio	Residence time (y)	Type**	Soil compartments	Temporal scale	Spatial scale	Scope
SOMM	L	-	Depends on microbial species, N and ash content in the substrate	A	2	Long term	Plot, field, global	Natural vegetation grazed ecosystem, forest ecosystem.
	F	-						
	H	-						
Ecosys	Plant residue			C		Short and Long term	Plot, field	Arable ecosystem in cold temperate and warm temperate subtropical climate
	Animal manure							
	Particulate SOM							
	Non-particulate							
RZWQM	Metabolic	80.0		C	Up to 12 layers	Short and Long term	Plot, field	Arable ecosystems
	Structural	8.0						
	Fast O.M.	8.0						
	Intermediate O.M	10.0						
	Slow O.M.	11.0						

[*] DPM - Decomposable plant material; SPM - Structural plant material; RPM - Resistant plant material; BIOM - Microbial biomass; AOM - Active organic matter; POM - Protected AOM; NOM - Non protected AOM; SOM - Stabilized organic matter; RO - Residual organic matter; BIO - Microbial biomass; HUM - Humus; FOM - Fresh organic matter; BOM - Biologically active soil organic matter; SOM – (Slow cycling) soil organic matter; IOM - Inert organic matter; MB - Microbial biomass; AOM1, SMB1 and SOM1 - Added organic matter, Soil microbial biomass and Soil organic matter with slow turn over, respectively; AOM2, SMB2 and SOM2 - Added organic matter, Soil microbial biomass and Soil organic matter with fast turn over, respectively; L - Undecomposed litter; F - Litter impregnated by humic substances; H - Humic substances of mineral top soil.

[**] Type: C - Comprehensive, S - Summary, A - Analytical.

component models (e.g., ANIMO, DAISY, SUNDIAL, RothC, CANDY, and CENTURY) show a similar basic structure, with a variable number of pools of fresh organic matter (residues), old(er, more stable) organic matter and microbial biomass. The decomposition rate constants of these different pools have generally been derived from fitting the models to experimental data, with or without tracers from incubations and/or (long-term) field experiments (Paustian, 1994). In the 'van Veen and Frissel' and 'Verberne' models, DAISY and DNDC, three residue pools are distinguished: a readily decomposable pool, a pool of structural (cell wall) material, and a pool of resistant lignified residues; the description in PAPRAN is conceptually comparable, as the chemical composition of the labile pool is used as an additional characteristic. The microbial biomass, if present, is either represented by a single pool (e.g.: the 'Juma and Paul' model, RothC, SUNDIAL, and APSIM) or by two: labile (non-protected) and stable (protected) (e.g., DAISY, DNDC, SOCRATES, 'Verberne' and NICCE). In CENTURY, the microbial biomass is combined with microbial metabolites and 'other' SOM with a relatively short turnover time in the active SOM pool. In PAPRAN, ANIMO and CANDY microbial biomass is considered part of the labile SOM pool, under the assumption that, although the microbial biomass plays a key role in the transformations of organic components in the soil, it comprises only a small portion of the total organic carbon pool (Ladd and Foster, 1988; Anderson and Domsch, 1989). Its intra-seasonal dynamics may be relevant in nitrogen dynamics, but the biomass is more or less constant when looking at inter-seasonal dynamics (Seligman and van Keulen, 1981; van Veen et al., 1984). In PAPRAN, SUNDIAL, CANDY, EPIC, APSIM and SOCRATES, a single pool of 'stable' SOM is defined (in RothC also a single dynamic SOM pool (humified organic matter) is defined, in addition to a small inert pool), in 'Verberne' and DAISY two, labile and stable, whereas in CENTURY, DNDC and NICCCE a third, more resistant or passive pool is distinguished. Even though these models seemingly differ in their conceptual pools, relative rates of decomposition and description of processes, they all appear capable of satisfactorily describing the dynamic behavior of soil organic matter (Jenkinson et al., 1987; Paustian et al., 1992; Parton and Rasmussen, 1994). For example, in CENTURY and RothC different conceptual pools are distinguished (active, slow and passive in CENTURY and humus and inert in RothC), with widely different residence times (few months, 25 years, 1 000 years in CENTURY, and 50 and 50 000 years in RothC). CENTURY's passive pool is larger than the inert organic matter (IOM) pool of RothC, both of which are resistant to decay. However, the active and the slow components in CENTURY and the BIOmass and HUMus components in RothC are of the same order of magnitude, so that both models are able to satisfactorily reproduce experimental results (Coleman et al., 1997; Kelly et al., 1997; Smith et al., 1997; Falloon and Smith, 2002). When RothC was coupled to CENTURY to generate plant C inputs, the SOC levels were underestimated, indicating an underestimation of SOC by CENTURY and/or a more rapid turnover of C in RothC (Falloon and Smith, 2002).

SOM turnover and stabilization of organic carbon inputs are influenced by both biotic (composition of plant residues: lignin and polyphenol contents) and abiotic (moisture, temperature, aeration, soil texture, and N availability) factors. Most of the reviewed models include these factors through reduction functions (Table 3) that modify the decomposition rates through the 'law of the minimum' or through a multiplicative concept.

When sub-optimal conditions are taken into account in a multiplicative way, the rate of decomposition of organic matter can be expressed as:

$$dY/dt = Y\ k\ [Tm\ Wm\ Om]$$

where Tm and Wm represent the reduction factors (between 0 and 1) for decomposition associated with sub-optimal soil temperature and moisture conditions. Om represents the reduction associated with sub-optimal conditions for other factors such as C/N ratio, pH, etc. Using this multiplicative concept may lead to relatively strong 'effective' reduction. For example, if the individual reduction factors are of a similar order of magnitude, for example, 0.75, 0.8 and 0.85, their interactive effect calculated in a multiplicative way equals 0.51, compared to 0.75 according to the law of the minimum. As the models are generally calibrated on the basis of empirical data,- it is difficult to experimentally establish the best approach.

In an extensive evaluation of SOM models (Smith et al., 1997), model performance was assessed both qualitatively and quantitatively in comparison to a number of experimental data sets. On the basis of 'performance', two groups could be distinguished; model errors of one group (ROTHC, CANDY, DNDC, CENTURY, DAISY and NCSOIL) were mutually comparable, as were those of the other group (SOMM and 'Verberne'), but the latter showed significantly larger deviations. One of the reasons for the poor performance of the second group was their inability to simulate processes associated with land uses that were different from those for which they were developed. This implies that our understanding of these processes is still incomplete and that model development, including calibration/validation, should be system-specific, i.e. the models need to be developed and calibrated taking into account the specific characteristics of each system. In the following section, the processes are identified relevant to the long-term dynamics of carbon and nitrogen in

Table 3. Description of temperature (Tm) and moisture functions (Wm) used by some models for modification of relative decomposition rate (k).

Model	Soil/air Temperature (°C)	Tm	Water content	Wm	Rate modification
APSIM	soil	$(T/T_{opt})^2$	θv	Increases from 0 to 1 between LL and 0.5 (LL+DUL), then 1 until DUL, then decreases to 0.5 at SAT	k Tm Wm
CENTURY	soil	$0.125\ e^{(0.07\ T)}$	SW*	If SW< 1.5, $1/[1+30\ e^{(-8.5\ SW)}]$ else 1-0.7(SW-1.5)/1.5	k Tm Wm
ANIMO	soil	$e^{[-\mu/R\ (1/(T+273)-1/(Tref+273))]}$	RWC pF<3.2 3.2< pF< 4.2 PF>4.2	$1/[1+4\ e^{(-6\ RWC)}]$ 1 1-0.8 (pF-3.2) 0.2	k Tm Wm
DNDC	soil	$((60-T)/25.78)^{3.503} * e^{(3.503\ (T-34.22)\ /\ 25.78)}$	WFPS	If WFPS > 0.05 1.01-0.21 WFPS else 0.0	-
RothC	air	$47.9/[1+e^{106/(T+18.3)}]$	TSMD	MIN (1, 0.2 + 0.8 (Clay factor-TSMD)/ 16.53)	-

T= average temperature; T_{ref} = reference temperature (25^0C); T_{opt} = optimum temperature for decomposition (30^0C); θv = volumetric water content; SW= (stored water + rainfall)/PET; PET= Potential evapo-transpiration; RWC= Relative water content; WFPS = Water-filled porosity; TSMD= Total soil moisture deficit; LL = lower limit of water content or Permanent wilting point; DUL= Water content at drained upper limit or field capacity; SAT= saturation water content; μ= molar activation energy (74826 $Jmol^{-1}$); R= gas constant (8.314 J mol^{-1} K^{-1}).
*Not compared in this study (Figure 3) since other soil and climatic characteristics are involved.

flooded rice-based cropping systems characterized by alternating wet and dry conditions.

Identifying processes relevant to long-term soil organic matter dynamics in rice-based cropping systems

A process-based approach for simulation of carbon and nitrogen dynamics under aerobic conditions most commonly includes the processes of decomposition of organic substrates and organic matter, growth and death of microbial biomass, nitrification, immobilization, denitrification, volatilization, leaching of NO_3^-, erosion, run off and crop uptake. When we analyze these processes under anaerobic conditions, their intensities differ, and other processes become more important, such as methanogenesis. A major problem associated with modeling C and N dynamics in flooded rice-based cropping systems is the weak linkage between-C/N-ratios of the substrate and gross mineralization rates (Reichardt et al., 2000; Devêvre and Horwáth, 2001; Ve et al., 2004a, b).

Typically, a rice soil is puddled at the start of the growing season and subsequently maintained under flooded conditions, creating two distinct zones in the soil profile: an upper puddled layer (0-15 cm), and a lower non-puddled layer. Hence, a description of the soil profile in a flooded rice system should comprise at least two layers: an upper homogenous zone characterized by a fully or partially reduced environment and a largely reduced lower zone. Carbon and nitrogen dynamics in soils under rice-based cropping systems that are permanently (rice-rice) or alternately (rice-upland crop) flooded largely depend on the length and frequency of the aerobic and anaerobic phases. In the short term (days), rates of decomposition of organic substrates under aerobic and anaerobic conditions are similar, but in the long term (seasons and years), decomposition rates under anaerobic conditions appear to be lower (Dobermann and Witt, 2000; Bird et al., 2003). Carbon mineralization was found to be three times slower under anaerobic than under aerobic conditions (DeBusk and Reddy, 1998). This slower decomposition rate, because of slower lignin degradation and the associated enrichment of young humus with phenolic compounds, partially explains the relatively stronger accumulation of organic matter in wetland soils. With an increasing number of annual irrigated rice crops, the phenolic nature of the humic acid fraction in soil increases (Olk et al., 1996). Microbial dynamics play a key role in C and N dynamics, as microbes are the active agents in SOM decomposition. Microbial biomass fluctuates under the influence of varying environmental conditions and substrate availability. Under aerobic conditions, aerobic microorganisms, especially fungi, dominate the soil microbial biomass and release phenols from decomposing lignin. Anaerobic microorganisms also decompose aromatic compounds such as phenols, but use different pathways (Evans, 1977). The phenolic structures liberated from parent lignin molecules often have a longer residence time in anaerobic soil than in aerobic soil and thus have more chance of polymerizing with some other component of SOM; consequently, SOM formed under submerged conditions undergoes stronger polymerization.

Processes of nitrogen dynamics, such as nitrification, immobilization, volatilization, denitrification and leaching occur in both aerobic and anaerobic situations at varying levels of intensity, depending on other soil conditions. Ammonium nitrogen, formed through mineralization from SOM is converted to NO_3^- (nitrification), at a rate depending on the oxidizing conditions in a soil. In lowland rice systems, under flooded conditions, the major part of mineral N is in NH_4^+-form (Mengel et al., 1986), because of the anaerobic conditions in the soil. The rates of nitrogen losses through complex processes, such as ammonia volatilization and denitrification depend on soil pH, moisture content and temperature. The major form of nitrogen losses in flooded rice soils is volatilization, as ammonia is the major form; significant nitrate losses can occur, when nitrate accumulated during fallow or upland conditions is lost through denitrification and/or leaching upon reflooding of the field for the next rice crop (George et al., 1993; Witt et al., 1998). In a long-term perspective, however, these complex processes of nitrogen dynamics can be combined into an overall loss fraction, the complement of the nitrogen recovery fraction (NRF). NRF of a fertilizer in a soil is the proportion of the applied fertilizer-N taken up by the crop, which may vary widely, in dependence of fertilizer type, method and timing of application (De Datta, 1986) and environmental conditions, i.e. soil, weather (van Keulen, 1982; 1986). Many experiments, in some of which ^{15}N was used to determine fertilizer recovery, have reported losses of fertilizer N in cereal cropping systems from 20 to 50%; such losses being attributed to a combination of denitrification, volatilization and leaching (van Keulen, 1982; 1986; Olson and Swallow, 1984; Sanchez and Blackmer, 1988; Francis et al., 1993; Wienhold et al., 1995; Karlen et al., 1996; Witt, 2003), as the individual processes are difficult to measure. Immobilization is the process that temporarily incorporates N in microbial biomass, which is followed by mineralization upon decay of the microbial biomass. Hence, immobilization can be ignored when considering the dynamics of carbon and nitrogen on a long-term basis. Run-off and soil erosion losses depend on the slope of the field and field length and on crop management. In puddled rice, with bunds around the fields, runoff losses and erosion are generally negligible and thus N losses through these processes can be omitted, apart from exceptional-situations, for instance on very steep slopes. Methane (CH_4) emission from flooded rice soils is a form of carbon loss resulting from extremely reduced conditions (Eh –150 to –250 mV) (Neue et al., 1990; Wang et al., 1993) and depends on the availability of easily decomposable substrates, such as root exudates, finer roots, incorporated green matter and labile SOM. Recent studies (Denier van der Gon et al., 2002; Sass and Cicerone, 2002) have shown an inverse relationship between a rice plant's grain filling potential and methane emission. By allocating more assimilated carbon to grains, methane production reduces proportionally. Low soil organic carbon content in many of the areas of the IGP, where rice-based cropping systems are practiced, have found low methane emission (Jain et al, 2000).

Crop N uptake depends, in addition to its availability, on crop N demand and soil moisture conditions. Crop N demand varies with crop development stage. At any stage, insufficient available N to meet crop demand will result in reduced biomass production and crop yield. Furthermore, reduced biomass production reduces C addition to the soil through roots, rhizodeposition and residues. Therefore, a crop growth model is required to quantitatively estimate crop N demand and the yield reductions associated with reduced N availability and to quantify organic additions to the soil.

Suitability of existing SOM models

To select a model for studying SOM turnover and carbon dynamics in a land use system from the available models, FAO (2004) proposed a set of procedures. These include starting from the SOMNET website, identifying the criteria for model selection, iteratively narrowing down to few models and studying these models in detail to identify the most suitable one. Following these steps, with the main selection criteria the processes relevant to the long-term dynamics of carbon and nitrogen in rice-based cropping systems of the Indo-Gangetic Plains (IGP) of India, we selected from the models treated above DNDC, ANIMO, CENTURY, RothC and APSIM. DNDC and ANIMO have the capability to simulate anaerobic soil conditions, which is relevant to the rice-based systems; CENTURY and RothC have the capability to simulate long-term SOM dynamics in arable agro-ecosystems; APSIM is suitable for modeling cropping systems involving sequences of crops, such as rotations, or mixtures of crops (Kirschbaum et al., 2001) and includes a routine for simulation of in-situ decomposition of added residues that is prevalent in rice-based cropping systems of South-Asia.

A rice-based cropping system, characterized by a puddled and flooded soil during part of the year, needs at least two layers to represent its profile. The single compartment concept of CENTURY and RothC assuming a uniform layer to a depth of 20 cm is thus not an appropriate representation of such a system. A fixed number of soil compartments, such as in DNDC (10 layers of 5 cm each) makes the model more comprehensive, but is also more demanding in terms of soil characteristics for different soil depths that may not be measured routinely. A user-defined number of soil compartments, taking into account the soil characteristics of the region as in ANIMO and APSIM would be a feasible option.

The number of carbon pools required to adequately describe the carbon turnover in any system is a compromise between the minimum needed to represent the varying rates of decomposition of SOM, considering its biochemical characteristics, and the temporal scale of the simulation. Mostly, these pools are defined on the basis of the objective(s) of the study. A comprehensive model, aimed at studying the processes in detail, requires a larger number of pools than a summary model aiming at satisfactory description of SOM dynamics. ANIMO allows definition of a number of materials classified into a number of classes and DNDC distinguishes three residue pools, two microbial pools and three SOM pools. In CENTURY, five pools are distinguished, i.e. two residue pools and three SOM pools. A small number of pools, as in APSIM (one residue pool and two SOM pools), requires less parameters for the model. The time constants or residence times (τ) for the various pools (Table 2) in these models also vary. The longest residence times for the pools in CENTURY (passive SOM) and RothC (inert SOM) are 2000 and 50 000 years, respectively. However, the longest residence times for the pools in ANIMO, APSIM and DNDC are in the range of 0.5-18 years only. The CENTURY and RothC models with pools of higher τ simulate the processes in a monthly time step, whereas the other three models (DNDC, APSIM and ANIMO) use a daily time step.

Rate modifications for the various residue and SOM pools, associated with sub-optimal environmental conditions, are generally calculated using-monthly or daily mean temperature (air or soil) and moisture conditions (Table 3, Figures 2 and 3), though other factors, such as soil texture, pH, C/N ratio and aeration are also included in some of these models. In APSIM, the temperature factor is calculated based on the optimum temperature (T_{opt}) for microbial growth (Table 3). CENTURY, DNDC and RothC calculate the effect of temperature through exponential functions. In ANIMO, the temperature factor is calculated using the Arrhenius equation with a reference temperature (T_{ref}) equal to the average annual temperature of the site. In APSIM and ANIMO, the effect of moisture conditions is described on the basis of volumetric moisture content and pF–value, respectively (Figure 2). In ANIMO, the pF value also

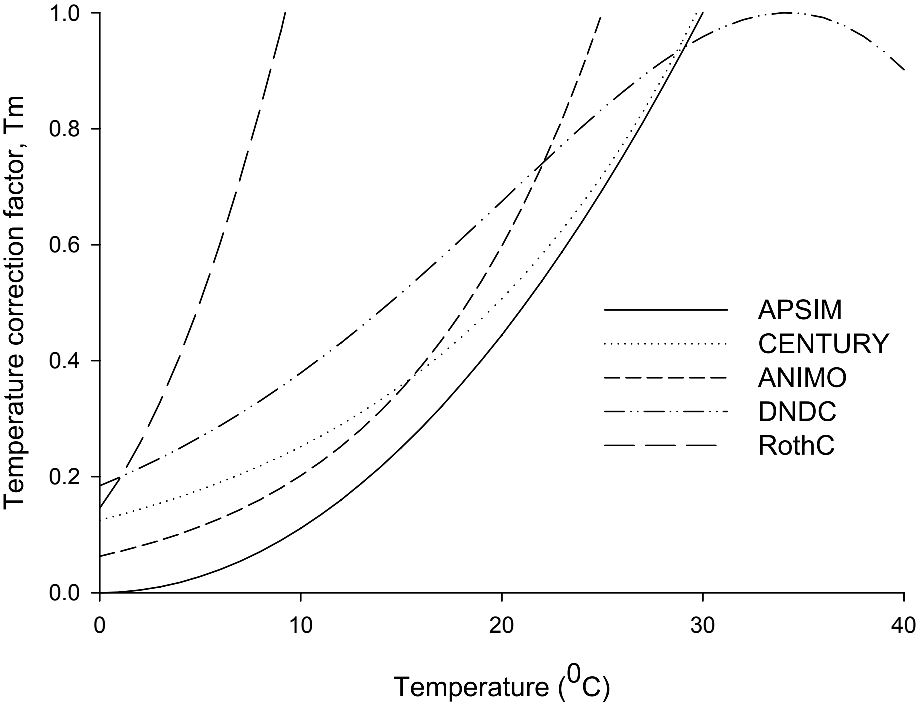

Figure 2. Temperature correction factor (Tm) for the rate of decomposition of SOM (lines have been drawn by restricting correction factor up to a value of 1).

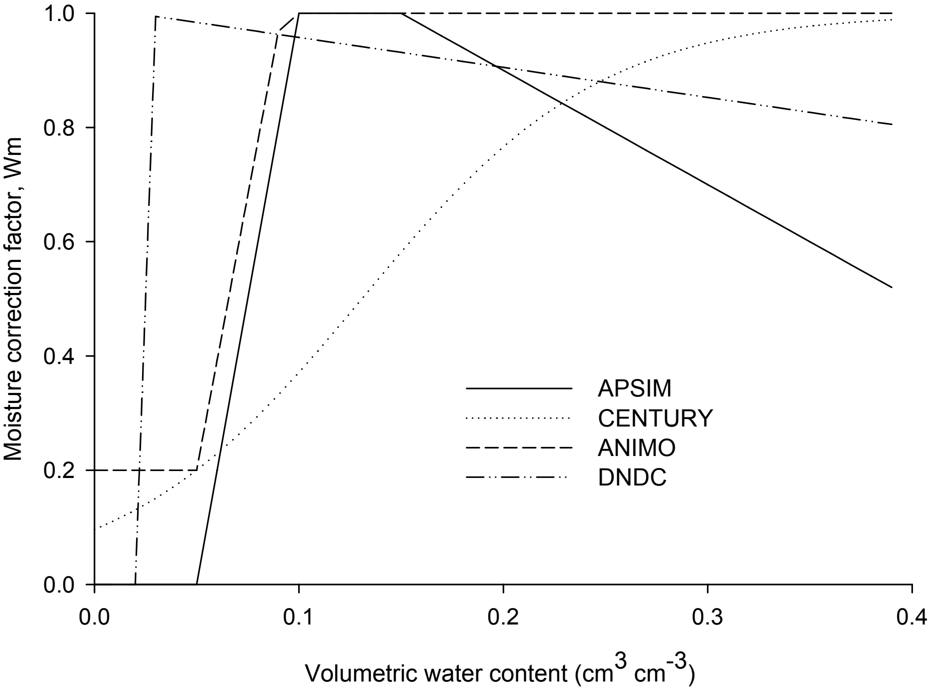

Figure 3. Moisture correction factor (Wm) for SOM decomposition (for a sandy soil) (conditions for which curves are drawn with water contents (cm^3 cm^{-3}) at LL= 0.05; DUL=0.15; and SAT = 0.4).

determines the degree of aeration of the soil that affects decomposition (Kroes and Roelsma, 1998). In RothC, total soil moisture deficit (TSMD), the accumulated difference of rainfall and evapo-transpiration over the simulation period, and maximum soil moisture deficit (MSMD), a characteristic derived from soil texture, determine the effect of moisture on SOM decomposition. Actual soil moisture content does not directly influence this rate. In earlier versions of CENTURY, the ratio of total available water (sum of monthly precipitation and initial soil moisture) and potential evapo-transpiration was used to modify decomposition rate; recent versions use RWC[§]. The interactive effect of temperature and moisture on the decomposition rate is calculated in all of these models in a multiplicative way (Table 3).

Inorganic nitrogen transformations are important in an alternately flooded and drained soil system in which the main form of N (NH_4^+ and NO_3^-) changes with changes in soil moisture regime. The decomposition sub-model in DNDC calculates nitrification, movement of nitrate and ammonium through the soil profile, ammonia volatilization, carbon dioxide and other greenhouse gas emissions. In the denitrification sub-model, denitrification and nitrous oxide (N_2O), nitric oxide (NO) and molecular nitrogen (N_2) production during wet periods are calculated at hourly intervals. ANIMO and APSIM also include detailed N transformation processes, such as volatilization, immobilization, nitrification and denitrification. In the N-submodel of CENTURY, N flows are derived from carbon flows and a fixed C/N ratio of the specific pool. However, when emphasizing long-term dynamics, inorganic N transformations may be less important, although substantial N losses may occur during the transition from flooded to aerobic conditions and vice-versa (Craswell and Vlek, 1979) and these need to be quantified. In CENTURY, focusing on long-term effects, N losses are set to 5% of the total N mineralized (leaching is considered negligible), which seems a suitable approach in this situation, where process descriptions of volatilization and denitrification are difficult to include because of their small time constants.

Proper estimation of biomass production and residue return to the soil is an important part of any SOM model. Detailed crop growth models, coupled to a SOM model, as in APSIM may be more accurate for this purpose. However, in long-term simulations, simple approaches rooted in a more comprehensive approach as in CENTURY, DNDC and RothC seem more appropriate. In CENTURY, biomass production is derived from annual precipitation, corrected for mineral N availability on the basis of the required C/N ratio for the plant material produced. In DNDC, potential biomass production is

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[§] Relative water content: the ratio of (actual water content minus water content at lower limit) and (water content at upper limit minus water content at lower limit) derived from a generalized crop growth curve, modified to actual production based on N-availability.

Many of these models also consider the effects of soil management such as tillage, residue cover or mulching on SOM decomposition and have been shown to be able to reproduce observed results in terms of the dynamics of C and N under various land use systems (Jenkinson et al., 1987; Rijtema and Kroes, 1991; Paustian et al., 1992; Li et al., 1994; 2003; Smith et al., 1997; Probert et al., 1998). Hence, comprehensive and summary models, considering the essential processes of C and N dynamics, such as SOM decomposition, crop growth, soil water and N dynamics, and environmental factors are adequate for quantitatively describing the short- as well as long-term dynamics of SOM. Considering the specific conditions in rice-based cropping systems, where changes in SOM quality (that is closely related to N-availability in the soil) appear equally important to changes in quantity, a simulation model including effects of quality (phenolic-humic nature) is necessary for a more complete description of SOM dynamics.

Concluding remarks

A wide variety of deterministic, multi-component (i.e. distinguishing a variable number of pools that differ in rate of decomposition) SOM models has been developed over the past three decades, illustrating (again) that, for various reasons, re-use of models is still a rare phenomenon (Donatelli et al., 2003). Most of these models have been developed, calibrated and applied for aerobic situations. Many estimate crop nitrogen supply (indigenous soil nitrogen supply) on the basis of SOM- and total-N content; however, under anaerobic conditions this relation appears weak, which may be related to the chemical characteristics of SOM. With increasing cropping intensity under flooded conditions, the phenolic nature of the humic acid fractions in soil increases, which contributes to the apparent decline in native soil N supply and yield in continuously cropped lowland rice soils. However, even though organic matter is found to accumulate under rice systems in long-term experiments, very few studies have been conducted to characterize SOM quality or its chemical nature. Results of preliminary studies (Olk, IRRI, pers. comm.; Yadvinder Singh et al., 2004) on the quality of SOM under rice crops in rotation with an upland crop (rice-wheat) indicate that the phenolic nature of labile SOM is more similar to that from lowland rice soils than from upland rice soils. Until now, approaches to describe SOM dynamics have focused mainly on the quantitative description of organic carbon and its dynamics, and did not consider (changes in) bio-chemical quality (phenolic-humic nature) and its effect on yield. Thus, there appears a need to develop a summary model that, in addition to the long-term carbon and nitrogen dynamics in lowland rice systems or alternating aerobic and anaerobic systems, pays attention to their quality.

References

Aggarwal, P.K., Bandhoyapadhyay, S.K., Pathak, H., Kalra, N., Chander, S. and Kumar, S., 2000. Analyses of yield trends of the rice-wheat system in north-western India. Outlook on Agriculture, 29: 259-268.

Ahuja, L.R., Hanson, J.D., Rojas, K.W. and Shaffer, M.J., 1999. Model overview. In: L.R. Ahuja, K.W. Rojas, L.D. Hanson, M.J. Shaffer and L. Ma (Eds.), The Root Zone Water Quality Model. Water Resources Publications LLC, Highlands Ranch, CO., pp. 1-12.

Allison, F.E., 1973. Soil organic matter and its role in crop production. Elsevier Science, New York.

Anderson, T. and Domsch, K.H., 1989. Ratios of microbial biomass carbon to total organic carbon in arable soils. Soil Biology and Biochemistry, 21: 471-479.

Andrén, O. and Kätterer, T., 1997. ICBM- the Introductory Carbon Balance Model for exploration of soil carbon balances. Ecological Applications, 7: 1226-1236.

Bird, J.A., van Kessel, C. and Horwáth, W.R., 2003. Stabilization of 13C-carbon and immobilization of 15N-nitrogen from rice straw in humic fractions. Soil Science Society of America Journal, 67: 806-816.

Bradbury, N.J., Whitmore, A.P., Hart, P.B.S. and Jenkinson, D.S., 1993. Modelling the fate of nitrogen in crop and soil in the years following application of 15N-labelled fertilizer to winter wheat. Journal of Agricultural Science, 121: 363-379.

Cassman, K.G. and Pingali, P.L., 1995. Extrapolating trends from long-term experiments to farmer's fields: The case of irrigated rice systems in Asia. In: V. Barnett, R. Payne and R. Steiner (Editors), Agricultural sustainability. Economic, environmental and statistical considerations. John Wiley and Sons, Chichester, pp. 63-84.

Chertov, O.G. and Komarov, A.S., 1996. A model of soil organic matter and nitrogen dynamics in terrestrial ecosystems. In: D.S. Powlson, P, Smith and J.U. Smith (Eds.), Evaluation of soil organic matter models using existing long-term datasets. Proceedings of the NATO Advanced Research workshop, NATO ASI Series I, Vol. 38, Springer-Verlag, Berlin, pp. 231-236.

Chertov, O.G. and Komarov, A.S., 1997. SOMM - a model of soil organic matter dynamics. Ecological Modelling, 94: 177-190.

Coleman, D.C., Oades, J.M. and Uehara, G., 1989. Dynamics of soil organic matter in tropical ecosystems. University of Hawaii Press, Honolulu.

Coleman, K. and Jenkinson, D.S., 1996. RothC-26.3-a model for the turnover of carbon in soil. In: D.S. Powlson, P. Smith and J.U. Smith (Eds.), Evaluation of soil organic matter models using existing long-term datasets. Proceedings of the NATO Advanced Research workshop, NATO ASI Series I, Vol. 38, Springer-Verlag, Berlin, pp. 237-246.

Coleman, K., Jenkinson, D.S., Crocker, G.J., Grace, P.R., Klir, J., Körschens, M., Poulton, P.R. and Richter, D.D., 1997. Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. Geoderma 81: 29-44.

Cornelissen, A.G.M., 2003. The two faces of sustainability. Fuzzy evaluation of sustainable development. Ph.D. Thesis, Wageningen University, Wageningen, The Netherlands.

Craswell, E.T. and Vlek, P.L.G., 1979. Fate of fertilizer nitrogen applied to wetland rice. In: Nitrogen and rice. International Rice Research Institute, Los Banõs, pp. 175-192.

Dawe, D., A. Dobermann, J.K. Ladha, R.L. Yadav, Lin Bao, R.K. Gupta, P. Lal, G. Panaullah, O. Sariam, Y. Singh, A. Swarup & Q. X. Zhen, 2003. Do organic amendments improve yield trends and profitability in intensive rice systems? Field Crops Research, 83: 191-213.

Dawe, D., Dobermann, A., Moya, P., Abdulrachman, S., Bijay Singh, Lal, P., Li, S.Y., Lin, B., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., Tan, P.S. and Zhen, X.Q., 2000. How widespread are yield declines in long-term rice experiments in Asia? Field Crops Research, 66: 175-193.

DeBusk, W.F. and Reddy, K.R., 1998. Turnover of detrital organic carbon in a nutrient-impacted Everglades marsh. Soil Science Society of America Journal, 62: 1460–1468.

De Datta, S.K., 1986. Improving nitrogen fertilizer efficiency in lowland rice in tropical Asia. Fertilizer Research, 9: 171-186.

Denier van der Gon, H.A.C., Kropff, M.J., van Breemen, N., Wassmann, R., Lantin, R.S., Aduna, E., Corton, T.M. and van Laar, H.H., 2002. Optimizing grain yields reduces CH_4 emissions from rice paddy fields. PNAS 99: 12021-12024.

Devêvre, O.C. and Horwáth, W.R., 2001. Stabilization of fertilizer nitrogen-15 into humic substances in aerobic vs. waterlogged soil following straw incorporation. Soil Science Society of America Journal, 65: 499-510.

Dobermann, A. and Witt, C., 2000. The potential impact of crop intensification on carbon and nitrogen cycling in intensive rice systems. In: G.J.D. Kirk and D.C. Olk (Eds.), Carbon and nitrogen dynamics in flooded soils. Proceedings of the workshop on Carbon and Nitrogen Dynamics in Flooded Soils, International Rice Research Institute, Los Banõs, pp. 1-25.

Dobermann, A., Dawe, D., Roetter, R.P. and Cassman, K.G., 2000. Reversal of rice yield decline in a long-term continuous cropping experiment. Agronomy Journal, 92: 633-643.

Donatelli, M., van Ittersum, M.K., Bindi, M. and Porter, J.R., 2003. Modelling cropping systems– highlights of the symposium and preface to the special issues. European Journal of Agronomy, 18: 1-11.

Esser, G., 1991. Osnabruck Biosphere Model: structure, construction, results. In: G. Esser and D. Overdieck (Eds.), Modern Ecology: basic and applied aspects. Elsevier, Amsterdam and London, pp. 679-709.

Esser, G., 1987. Sensitivity of global carbon pools and fluxes to human and potential climatic impacts. Tellus, 39B: 459-476.

Evans, W.C., 1977. Biochemistry of the bacterial catabolism of aromatic compounds in anaerobic environments. Nature, 270: 17-22.

Falloon, P. and Smith, P., 2002. Simulating SOC dynamics in long-term experiments with RothC and CENTURY: model evaluation for a regional scale application. Soil Use and Management, 18: 101-111.

FAO, 2004. Assessing carbon stocks and modelling win-win scenarios of carbon sequestration through land use changes. FAO, Rome.

Francis, D.D., Schepers, J.S. and Vigil, M.F., 1993. Post-anthesis nitrogen loss from corn. Agronomy Journal, 85: 659-663.

Franko, U., 1996. Modelling approaches of soil organic matter turnover within the CANDY system. In: D.S. Powlson, P. Smith and J.U. Smith (Eds.), Evaluation of soil organic matter models using existing long-term datasets. Proceedings of the NATO Advanced Research workshop, NATO ASI Series I, Vol. 38, Springer Verlag, Berlin, pp. 247-254.

Franko, U., Oelschlägel, B. and Schenk, S., 1995. Simulation of temperature, water- and nitrogen dynamics using the model CANDY. Ecological Modelling, 81: 213-222.

Frissel, M.J. and Van Veen, J.A., 1981. Simulation of nitrogen behaviour of soil-plant systems. Papers of a workshop: Models for the behaviour of nitrogen in soil and uptake by plant. Comparison between different approaches. Pudoc, Wageningen.

George, T., Ladha, J.K., Buresh, R.J. and Garrity, D.P., 1993. Nitrate dynamics in the aerobic soil phase in low-land rice-based cropping systems. Soil Science Society of America Journal, 57: 1526-1532.

Grace, P.R. and Ladd, J.N., 1995. SOCRATES (Soil Organic Carbon Reserves And Transformations in agro-Eco-Systems). CRC for Soil and Land Management, Adelaide.

Grace, P.R. and Merz, S.K., 2001. Net Ecosystem Exchange workshop proceedings. CRC for Greenhouse Accounting, Canberra.

Grant, R.F., 2001. A review of the Canadian Ecosystem model-Ecosys. In: M.J. Shaffer, L. Ma and S. Hansen (Eds.), Modeling carbon and nitrogen dynamics for soil management. Lewis Publishers, Boca Raton, FL, pp. 173-263.

Grant, R.F. and Rochette, P., 1994. Soil microbial respiration at different water potentials and temperatures - theory and mathematical-modeling. Soil Science Society of America Journal, 58: 1681-1690.

Grant, R.F., Juma, N.G. and McGill, W.B., 1993. Simulation of carbon and nitrogen transformations in soil - mineralization. Soil Biology and Biochemistry, 25: 1317-1329.

Grant, R.F., Juma, N.G., Robertson, J.A., Izaurralde, R.C. and McGill, W.B., 2001. Long-term changes in soil carbon under different fertilizer, manure, and rotation: Testing the mathematical model ecosys with data from the Breton plots. Soil Science Society of America Journal, 65: 205-214.

Hansen, S., Jensen, N.E., Nielsen, N.E. and Svendsen, H., 1990. DAISY- Soil Plant Atmosphere System Model. NPo-forskning fra Miljøstyrelsen A10, The Royal Veterinary and Agricultural University, Copenhagen,

Hart, P.B.S., 1984. Effects of soil type and past cropping on the nitrogen supplying ability of arable soils. Ph.D. Thesis, University of Reading, Reading.

Henin, S. and Dupuis, M., 1945. Essai de bilan de la matière organique du sol. Annals of Agronomy, 15: 17-29.

Izaurralde, R.C., Williams, J.R., McGill, W.B. and Rosenberg, N.J., 2001. Paper presented at the first National Conference on Carbon Sequestration organized by the U.S. Department of Energy-National Energy Technology Laboratory, held at the Renaissance Washington DC Hotel, Washington, DC, May 14-17, 2001.

Jain, M.C., Kumar, S., Wassmann, R., Mitra, S., Singh, S.D., Singh, J.P., Singh, R., Yadav, A. K., Gupta, S., 2000. Methane Emissions from Irrigated Rice Fields in Northern India (New Delhi). Nutrient Cycling in Agroecosystems, 58: 75-83.

Janssen, B.H., 1984. A simple method for calculating decomposition and accumulation of 'young' soil organic matter. Plant and Soil, 76: 297-304.

Janssen, B.H., 1986. Een één-parametermodel voor de berekening van de decompositie van organisch material. Vakblad voor Biologen, 66: 433-436.

Jenkinson, D.S., 1990. The turnover of organic carbon and nitrogen in soil. Philosophical Transactions of the Royal Society, London B, 329: 361-368.

Jenkinson, D.S. and Coleman, K.C., 1994. Calculating the annual input of organic matter to soil from measurements of total organic carbon and radiocarbon. European Journal of Soil Science, 45: 167-174.

Jenkinson, D.S. and Rayner, J.H., 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Science, 123: 298-305.

Jenkinson, D.S., Adams, D.E. and Wild, A., 1991. Model estimates of CO_2 emissions from soil in response to global warming. Nature, 351: 304-306.

Jenkinson, D.S., Hart, P.B.S, Rayner, J.H. and Parry, L.C., 1987. Modelling the turnover of organic matter in long-term experiments at Rothamsted. INTECOL Bulletin, 15: 1-8.

Jenkinson, D.S., Harkness, D.D., Vance, E.D., Adams, D.E. and Harrison, A.F., 1992. Calculating net primary production and annual input of organic matter to soil from the amount and radiocarbon content of soil organic matter. Soil Biology and Biochemistry, 24: 295-308.

Juma, N.G. and Paul, E.A., 1981. Use of tracer and computer simulation techniques to assess mineralisation and immobilisation of soil nitrogen. In: M.J. Frissel and J.A. van Veen (Editors), Simulation of nitrogen behaviour of soil-plant systems. Pudoc, Wageningen, pp. 145-154.

Karlen, D.L., Hunt, P.G. and Matheny, T.A., 1996. Fertilizer ^{15}N recovery by corn, wheat, and cotton grown with and without pre-plant tillage on Norfolk loamy sand. Crop Science, 36: 975-981.

Kätterer, T., Andrén, O. and Persson, J., 2004. The impact of altered management on long-term agricultural soil carbon stocks- a Swedish case study. Nutrient Cycling in Agroecosystems, 70: 179-187.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. European Journal of Agronomy, 18: 267-288.

Kelly, R.H., Parton, W.J., Crocker, G., Grace, P., Klir, J., Korschens, M., Poulton, P.R. and Richter, D.D., 1997. Simulating trends in soil organic carbon in long-term experiments using the CENTURY model. Geoderma, 81: 75-90.

Kirschbaum, M.U.F., Carter, J.O., Grace, P.R., Keating, B.A., Keenan, R.J., Landsberg, J.J., McKeon, G.M., Moore, A.D., Paul, K.I., Pepper, D.A., Probert, M.E., Richards, G.P, Sands, P.J. and Skjemstad, J.O., 2001. Brief description of several models for simulating net ecosystem exchange in Australia. Net Ecosystem Exchange workshop proceedings, CRC for greenhouse accounting, Canberra, 18-20 April, 2001.

Kolenbrander, G.J., 1969. De bepaling van de waarde van verschillende soorten organische stof ten aanzien van hun effect op het humusgehalte bij bouwland. Inst. Bodemvruchtb., Haren.

Kortleven, H., 1963. Quantitative aspects of humus accumulation and decomposition. Versl. Landbk. Onderz. 69.1, Pudoc, Wageningen.

Kroes, J.G. and Roelsma, J., 1998. ANIMO 3.5: user's guide for the ANIMO version 3.5 nutrient leaching model. SC-DLO, Techn. Doc. 46, Wageningen.

Kruseman, G., Hengsdijk, H. and Ruben, R., 1993. Disentangling the concept of sustainability. Conceptual definitions, analytical framework and operational techniques in sustainable land use. DLV report no. 2, CABO-DLO, Wageningen.

Ladd, J.N. and Foster, R.C., 1988. Role of soil microflora in nitrogen turnover. In: J.R. Wilson (Ed.), Advances in nitrogen cycling in agricultural ecosystems. CAB International, Wallingford, pp. 113-133.

Ladd, J.N., Amato, M., Grace, P.R. and Van Veen, J.A., 1995. Simulation of ^{14}C turnover through the microbial biomass in soils incubated with ^{14}C-labelled plant residues. Soil Biology and Biochemistry, 27: 777-783.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Bijay Singh, Yadvinder Singh, Singh, Y., Singh, P., Kundu, A. L., Sakal, A.R., Ram, N., Regmi, A. P., Gami, S. K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K. and Hobbs, P.R., 2003. How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crops Research, 81: 159-180.

Lal, R., 2002. Soil carbon sequestration in China through agricultural intensification, and restoration of degraded and deserted ecosystems. Land Degradation and Development, 13: 469-478.

Li, C., 1995. Modelling impact of agricultural practices on soil C and N_2O emissions. In: R. Lal, J. Kimble, E. Levine and B.A. Stewart (Eds.), Soil management and greenhouse effect. Advances in Soil Science. CRC Press, Inc., Boca Raton, FL,, pp. 101-112.

Li, C., Frolking, S. and Harriss, R.C., 1994. Modelling carbon biogeochemistry in agricultural soils. Global Biogeochemical Cycles, 8: 237-254.

Li, C., Narayanan, V. and Harriss, R.C., 1995. Nitrous oxide emissions in 1990 from agricultural lands in the United States. Global Biogeochemical Cycles, 10: 297–306.

Li., C., Zhuang, Y., Frolking, S., Galloway, J., Harriss, R., Moore III, B., Schimel, D. and Wang, X., 2003. Modelling soil organic carbon change in croplands of China. Ecological Applications, 13: 327-336.

Lieth, H., 1975. Modelling the primary productivity of the world. In: H. Lieth and R.H. Whittaker (Eds.), Primary Productivity of the Biosphere. Springer-Verlag, Berlin, pp. 237-263.

Ma, L. and Shaffer, M.J., 2001. A review of carbon and nitrogen processes in nine U.S. soil nitrogen dynamics models. In: M.J. Shaffer, L. Ma and S. Hansen (Eds.), Modeling carbon and nitrogen dynamics for soil management. Lewis Publishers, Boca Raton, FL, pp. 55-102.

Ma, L., Shaffer, M.J. and Ahuja, L.R., 2001. Application of RZWQM for soil nitrogen management. In: M.J. Shaffer, L. Ma and S. Hansen (Eds.), Modeling carbon and nitrogen dynamics for soil management. Lewis Publishers, Boca Raton, FL, pp. 265-301.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P. and Freebairn, D.M., 1996. APSIM: A novel software system for model development, model testing, and simulation in agricultural systems research. Agricultural Systems, 50: 255-271.

McGechan, M.B. and Wu, L., 2001. A review of carbon and nitrogen processes in European soil nitrogen dynamics models. In: M.J. Shaffer, L. Ma and S. Hansen (Eds.), Modeling carbon and nitrogen dynamics for soil management. Lewis Publishers, Boca Raton FL, pp. 103-171.

McGill, W., 1996. Review and classification of ten soil organic matter (SOM) models. In: D.S. Powlson, P. Smith and J.U. Smith (Eds.), Evaluation of soil organic matter models using existing long-term datasets. Proceedings of the NATO Advanced Research workshop, NATO ASI Series I, Vol. 38, Springer Verlag, Berlin, pp. 111-132.

Mengel, K., Schon, H.G., Keerthisinghe, G. and De Datta, S.K., 1986. Ammonium dynamics of puddled soils in relation to growth and yield of lowland rice. Fertilizer Research, 9: 117-130.

Molina, J.A.E. and Smith, P., 1998. Modelling carbon and nitrogen processes in soil. Advances in Agronomy, 62: 253-298.

Molina, J.A.E., Clapp, C.E., Shaffer, M.J., Chichester, F.W. and Larson, W.E., 1983. NCSOIL, a model of nitrogen and carbon transformations in soil: description, calibration, and behavior. Soil Science Society of America Journal, 47: 85-91.

Mueller, T., Jensen, L.S., Hansen, S. and Nielsen, N.E., 1996. Simulating soil carbon and nitrogen dynamics with the soil-plant-atmosphere system model DAISY. In: D.S. Powlson, P. Smith and J.U. Smith (Eds.), Evaluation of soil organic matter models using existing long-term datasets. Proceedings of the NATO Advanced Research workshop, NATO ASI Series I, Vol. 38, Springer Verlag, Berlin, pp. 275-281.

Narang, R.S. and Virmani, S.M., 2001. Rice-wheat cropping systems of the Indo-Gangetic Plain of India. Consortium Paper Series 11. Rice-wheat Consortium for the Indo-Gangetic Plains, New Delhi.

Neue, H.U., Heidmann, P.B. and Scharpenseel, H.W., 1990. Organic matter dynamics, soil properties, and cultural practices in rice lands and their relationship to methane production. In: A. F. Bouman (Ed.), Soil and the Greenhouse Effect. John Wiley & Sons, Chichester, pp. 457-466.

Noij, I.G.A.M., Janssen, B.H., Wesselink, L.G. and van Grinsven, J.J.M., 1993. Modelling nutrient and moisture cycling in tropical forests. In: Tropenbos Series 4, Tropenbos Foundation, Wageningen, pp. 15-26.

Olk, D.C., Cassman, K.G., Randall, E.W., Kinchesh, P., Sanger, L.J. and Anderson, J.M., 1996. Changes in chemical properties of soil organic matter with intensified rice cropping in tropical lowland soils. European Journal of Soil Science, 47: 293-303.

Olson, R.V. and Swallow, C.W., 1984. Fate of labeled nitrogen fertilizer applied to winter wheat for five years. Soil Science Society of America Journal, 48: 583-586.

Parnas, H., 1975. Model for decomposition of organic material by microorganisms. Soil Biology and Biochemistry, 7: 161-169.

Parton, W.J. and Rasmussen, P.E., 1994. Long-term effects of crop management in wheat fallow: II. CENTURY model simulations. Soil Science Society of America Journal, 58: 530-536.

Parton, W.J., Stewart, J.W.B. and Cole, C.V., 1988. Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry, 5: 109-131.

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal, 51: 1173-1179.

Paustian, K., 1994. Modelling soil biology and biochemical processes for sustainable agriculture research. In: C.E. Pankhurst, D.M. Doube, V.V.S.R. Gupta and P.R. Grace (Eds.), Soil Biota: Management in sustainable farming systems. CSIRO, Canberra, pp. 182-193.

Paustian, K., Parton, W.J. and Persson, J., 1992. Modelling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. Soil Science Society of America Journal, 56: 476-488.

Penning de Vries, F.W.T., 1982. Systems analysis and models of crop growth. In: F.W.T. Penning de Vries and H.H. van Laar (Eds.), Simulation of plant growth and crop production. Simulation Monographs, Pudoc, Wageningen, pp. 9-19.

Post, W.M., Izarurralde, R.C., Jastrow, J.D., McCarl, B.A.. Amonette, J.E.,-Bailey, V.L., Jardien, P.M., West, T.O. and Zhou, J. 2004. Enhancement of carbon sequestration in U.S. soils. BioScience, 54: 895-908.

Powlson, D. S. and Olk, D.C., 2000. Long-term soil organic matter dynamics. In: G.J.D. Kirk and D.C. Olk (Eds.), Carbon and nitrogen dynamics in flooded soils. Proceedings of the workshop on Carbon and Nitrogen Dynamics in Flooded Soils, International Rice Research Institute, Los Banõs, pp. 49-63.

Powlson, D.S., Smith, P. and Smith, J.U. (Eds.), 1996. Evaluation of soil organic matter models using existing long-term datasets. Proceedings of the NATO Advanced Research workshop, NATO ASI Series I, Vol. 38, Springer Verlag, Berlin.

Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C., and Strong, W.M., 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agricultural Systems, 56: 1-28.

Raijmakers, W.M.F. and Janssen, B.H., 1995. Evaluatie van methoden ter bepaling van voor de plant beschikbaar stikstof en fostaat in organische meststoffen. Eindrapportage van het project 'Plantevoedende waarde van organische mest en afvalverwerkingsprodukten'. Wageningen Agricultural University, Wageningen, pp. 104-111.

Ram Nand, 1998. Effect of continuous fertilizer use on soil fertility and productivity of a mollisol. In: A. Swarup, D.D. Reddy and R.N. Prasad (Eds.), Long-term soil fertility management through integrated plant nutrient supply. Indian Institute of Soil Science, Bhopal, pp. 229-237.

Ram, Nand 2000. Long-term effects of fertilizers on rice-wheat-cowpea productivity and soil properties in a Mollisol. In: Abrol, I.P., Bronson, K.F., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term soil fertility experiments with rice-wheat rotations in South Asia. Rice-Wheat Consortium Paper Series 6. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India. pp. 50-55.

Reichardt, W., Inubushi, K. and Tiedje, J., 2000. Microbial processes in C and N dynamics. In: G.J.D. Kirk and D.C. Olk (Eds.), Carbon and nitrogen dynamics in flooded soils. Proceedings of the workshop on Carbon and Nitrogen Dynamics in Flooded Soils, International Rice Research Institute, Los Banõs, pp. 101-146.

Rijtema, P.E. and Kroes, J.G., 1991. Some results of nitrogen simulations with the model ANIMO. Fertilizer Research, 27: 189-198.

Sanchez, C.A. and Blackmer, A.M., 1988. Recovery of anhydrous ammonia-derived ^{15}N during three years of corn production in Iowa. Agronomy Journal, 80: 102-108.

Sass, R.L. and Cicerone, R.J., 2002. Photosynthate allocations in rice plants: food production or atmospheric methane? PNAS, 99: 11993-11995.

Sauerbeck, D.R. and Gonzalez, M.A., 1977. Field decomposition of carbon-14-labelled plant residues in various soils of the Federal Republic of Germany and Costa Rica. In: Soil organic matter studies. Proceedings of a Symposium organized by IAEA, FAO and Agrochimica, Braunschweig. I, pp. 159-170.

Seligman, N.G. and Van Keulen, H., 1981. PAPRAN: a simulation model of annual pasture production limited by rainfall and nitrogen. In: M.J. Frissel and J.A. van Veen (Eds.), Simulation of nitrogen behavior of soil plant systems. Pudoc, Wageningen, pp. 192-220.

Smith, J.U., Bradbury, N.J. and Addiscott, T.M., 1996. SUNDIAL: Simulation of Nitrogen Dynamics in Arable Land. A user-friendly, PC-based version of the Rothamsted Nitrogen Turnover model. Agronomy Journal, 88: 38-43.

Smith, P., Falloon, P., Coleman, K., Smith, J.U., Piccolo, M., Cerri, C.C., Bernoux, M., Jenkinson, D.S., Ingram, J.S.I., Szabó, J. and Pásztor, L., 1999. Modelling soil carbon dynamics in tropical ecosystems. In: R. Lal, J.M. Kimble, R.F. Follett and B.A. Stewart (Eds.), Global Climate Change and Tropical Soils. Advances in Soil Science, CRC Press, Inc., Boca Raton, FL., pp. 341-364.

Smith, P., Powlson, D.S., Smith, J.U. and Elliott, T.E. (Eds.), 1997. Evaluation and comparison of soil organic matter models using long-term datasets. Geoderma, 81: 1-255.

Springer, U. and Lehner, A. Z., 1952. Organic matter decomposition and humus formation in the aerobic decomposition of agricultural and silvicultural important organic materials I: Zeits. Pflanzenernähr. Düng. Bodenk., 58: 193-231.

Van Dam, D. and Van Breemen, N., 1995. NICCCE- a model for cycling of nitrogen and carbon isotopes in coniferous forest ecosystems. Ecological Modelling, 79: 255-275.

Van Ittersum, M.K., Leffelaar, P.A., Van Keulen, H., Kropff, M.J., Bastiaans, L. and Goudriaan, J., 2002. Developments in modelling crop growth, cropping systems and production systems in the Wageningen School. Netherlands Journal of Agricultural Sciences, 50: 239-247.

Van Keulen, H., 2001. (Tropical) soil organic matter modelling: problems and prospects. Nutrient-Cycling in Agroecosystems, 61: 33-39.

Van Keulen, H., 1986. Crop yield and nutrient requirements. In: H. van Keulen and J. Wolf (Eds.), Modelling of agricultural production: weather, soils and crops. Simulation Monographs, Pudoc, Wageningen, pp. 154-181.

Van Keulen, H., 1982. Graphical analysis of annual crop response to fertiliser application. Agricultural Systems, 9: 113-126.

Van Veen, J.A. and Frissel, M.J., 1981. Simulation model of the behaviour of nitrogen in soil. In: M.J. Frissel and J.A.Van Veen (Eds.), Simulation of nitrogen behaviour of soil plant systems. Pudoc, Wageningen,-pp. 126-144.

Van Veen, J. and Paul, E.A., 1981. Organic carbon dynamics in grassland soils. 1. Background information and computer simulation. Canadian Journal of Soil Science, 61: 185-201.

Van Veen, J.A., Ladd, J.N. and Frissel, M.J., 1984. Modelling C and N turnover through the microbial biomass in soil. Plant and Soil, 76: 257-274.

Ve, N.B., Olk, D.C. and Cassman, K.G., 2004a. Characterization of humic acid fractions improves estimates of nitrogen mineralization kinetics for lowland rice soils. Soil Science Society of America Journal, 68: 1266-1277.

Ve, N.B., Olk, D.C. and Cassman, K.G., 2004b. Nitrogen mineralization from humic acid fractions in rice soils depends on degree of humification. Soil Science Society of America Journal, 68: 1278-1284.

Verberne, E.L.J., Hassink, J., De Willigen, P., Groot, J.J.R. and van Veen, J.A., 1990. Modelling organic matter dynamics in different soils. Netherlands Journal of Agricultural Sciences, 38: 221-238.

Wang, Z.P., De Laune, R.D., Masscheleyn, P.H., Patrick Jr., W.H., 1993. Soil redox and pH effects on methane production in a flooded rice field. Soil Science Society of America Journal, 57: 382-385.

Wienhold, B.J., Todd, P.T. and George, A.R., 1995. Yield and nitrogen use efficiency of irrigated corn in the Northern Great Plains. Agronomy Journal, 87: 842-846.

Williams, J.R., 1995. The EPIC model. In: V.P. Singh (Ed.), Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, CO., pp. 909-1000.

Witt, C., 2003. Fertilizer use efficiencies in irrigated rice in Asia. IFA Regional Conference for Asia and the Pacific, Cheju Island, Korea, 6-8 October 2003.

Witt, C., Cassman, K.G., Ottow, J.C.G. and Biker, U., 1998. Soil microbial biomass and nitrogen supply in an irrigated lowland rice soil as affected by crop rotation and residue management. Biology and Fertility of Soils, 28: 71-80.

Yadvinder Singh, Bijay-Singh, Ladha, J.K., Khind, C.S., Gupta, R.K., Meelu, O.P. and Pasuquin, E., 2004. Long-term effects of organic inputs on yield and soil fertility in the rice-wheat rotation. Soil Science Society of America Journal, 68: 845-853.

Yang, H.S., 1996. Modelling organic matter mineralization and exploring options for organic matter management in arable farming in Northern China. Ph.D. Thesis, Wageningen Agricultural University, Wageningen.

CHAPTER 3

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

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Abstract

Proper understanding of the soil carbon balance and of measures required to build up or maintain soil carbon status of agricultural production systems is important for their sustainable production. Long-term experiments are especially useful to gain understanding of soil carbon dynamics, since the processes affecting carbon dynamics are slow in nature. We used a simple analytical model (Yang, 1996; Yang and Janssen, 2000) to calculate carbon balances in the rice-based cropping systems of the Indo-Gangetic Plains (IGP) in India to evaluate model performance. Yang's model is simple in approach and needs two basic parameters: the initial relative mineralization rate (R) and the rate of ageing of a substrate (S). A rate-modifying factor for temperature is included in the model. We used eight data sets from rice-based cropping systems (rice-wheat rotations sometimes with a third crop) from different sub-regions in the IGP, with different levels of mineral fertilizers, green manures, farm yard manure (FYM), and residue treatments applied to rice, wheat or a third crop. Carbon input into the soil from crop biomass is a function of climate, soil and management factors, and was calculated using data on crop yield and harvest Index (HI). In chemically fertilized cropping systems in the IGP, residues are commonly not incorporated into the soil, and the major soil carbon source consists of roots and rhizodeposition. The added organic carbon, originating from root biomass and organic amendments, and the indigenous, stabilized soil organic carbon (SOC) undergo decomposition concurrently. The values of soil organic carbon content predicted by the model were comparable to the observed values ($R^2 = 0.81$). Periodic carbon balances were assessed on the basis of carbon inputs into and outputs from the system for successive periods of cropping. The model results in general followed the observed trends. The results of the study indicate that sites with initially low (≤ 5 g kg^{-1}) organic C contents show an increase under cultivation, since the organic carbon demand to maintain their initial level is low, whereas sites with relatively high SOC contents (>5 g kg^{-1}) decline under cultivation when only mineral fertilizers are applied. The study emphasizes the importance of adequate and repeated additions of carbon to maintain satisfactory soil organic carbon levels, a necessary condition for long-term sustainable cropping systems.

Keywords: Crop characteristics, rotations, soil carbon dynamics, Yang's model

Introduction

The Indo-Gangetic Plains (IGP) of India, comprising 13 percent of its total area, is important in food supply of the country, contributing nearly 50 percent to its total food-grain production. Crop production in the IGP is dominated by rice-based cropping systems, predominantly rice-wheat. Stimulated by an assured market, 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; Narang and Virmani, 2001; Bhandari et al., 2002; 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; Ladha et al., 2003). 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; Ram, 1995; 1998; Saha et al., 1998; Kundu and Samui, 2000; Prasad and Sinha, 2000; Saha et al., 2000; Yadvinder et al., 2000; Yaduvanshi, 2001). 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; Buyanovsky and Wagner, 1998; 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 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 (Jenkinson and Ayanaba, 1977; Pieri, 1989; Van Wambeke, 1992; Buyanovsky and Wagner, 1998). For example,

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

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; Havlin et al., 1990; Singh et al., 1998; Dersch and Bohm, 2001; Holeplass et al., 2004). Specific soil management practices, such as minimum tillage, reduce the rate of decomposition of SOC, and similarly improve the soil carbon balance.

Long-term experiments, yielding information on seasonal or annual biomass production and carbon content in the soil are useful in estimating soil carbon balances, provided the experimental results can be properly interpreted, e.g. by application of appropriate process formulations. After validation, such formulations can be used in models to evaluate crop and soil management. 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 apply the results to predict possible changes in the future.

Methodology

Basic data

The Indo-Gangetic Plains in India, extending from 21^0 45’ to 31^0 0’ N Latitude and 74^0 15’ to 91^0 30’ E Longitude (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. The LTEs cover a range of treatments, including different doses of chemical fertilizers, green manures, and farmyard manure (FYM), and different residue management practices applied to rice, wheat and/or a third crop (Table 1). Climate and soil characteristics of the various sites are given in Table 2.

Yang’s model

Following first order kinetics, the rate of decomposition of an organic substrate (dY/dt) and the quantity of the substrate at any time t, Y_t, can be described according to:

$$dY/dt = -k\,Y$$

$$Y_t = Y_0\,e^{-kt} \qquad (1)$$

where Y_0 is the initial quantity and k is the relative decomposition rate (y^{-1}). In this paper, the quantity Y refers to soil organic carbon and is expressed in the mass fraction of C in soil (g kg^{-1}).

Table 1. Cropping systems (CS) and treatments for the various sites used in the study.

Site	CS[1]	Duration	Tr.No	Treatments[2]			100% NPK fertilizer rate (kg ha^{-1})		
				Rice	Wheat	3rd crop	Rice	Wheat	3rd crop
Ludhiana-1	R-W	1988-2000	I.	WS+ GM+ N-52 kg ha^{-1}	100% NPK	-	150-0-0	90-26-50	-
			II.	N- 150 kg ha^{-1}	100% NPK	-			
			III.	No-NPK+ no-FYM	100% NPK	-			
Ludhiana-2	R-W	1993-2000	I.	100% NPK	RI-120N	-	120-26-25	120-26-25	-
			II.	100% NPK	RR-120N				
			III.	100% NPK	RR-0N	-			
Ludhiana-3	R-W	1983-1997	I.	50% NPK + 6 Mg ha^{-1} FYM	100%NPK	-	120-26-25	120-26-25	-
			II.	100% NPK	100%NPK	-			
			III.	No-NPK+ no-FYM	No-NPK+ no-FYM	-			
Karnal	R-W	1994-1999	I.	100% NPK+ 10 Mg ha^{-1} FYM	100% NPK	-	120-26-42	120-26-42	-
			II.	100% NPK	100% NPK	-			
			III.	No-NPK+ no-FYM	No-NPK+ no-FYM	-			
Samastipur	R-W	1988-1995	I.	100% NPK + 10 Mg ha^{-1} FYM	100% NPK	-	100-60-40	100-60-40	-
			II.	100% NPK	100% NPK	-			
			III.	No-NPK+ No-FYM	No-NPK+ No-FYM	-			
Pantnagar	R-W-C	1971-2000	I.	100% NPK+ 15 Mg ha^{-1} FYM	100% NPK	No-NPK	120-26-35	120-26-35	-
			II.	100% NPK	100% NPK	No-NPK			
			III.	No-NPK+ no-FYM	No-NPK+ no-FYM	No-NPK			
Barrackpore	R-W-J	1971-1995	I.	100% NPK	100% NPK	100% NPK+ 10 Mg ha^{-1} FYM	120-26-50	120-26-50	60-13-50
			II.	100% NPK	100% NPK	100% NPK			
			III.	No-NPK+ No-FYM	No-NPK+ No-FYM	No-NPK+ No-FYM			
Nadia	R-W	1986-1995	I.	50% NPK + 7.5 Mg ha^{-1} FYM	100% NPK	-	100-60-40	100-60-40	-
			II.	100% NPK	100% NPK	-			
			III.	No-NPK+ No-FYM	No-NPK+ No-FYM	-			

1 R-W: Rice-Wheat; R-W-C: Rice-Wheat-Cowpea; R-W-J: Rice-Wheat-Jute.

2 RR-0N: Rice residue Removed with no fertilizer-N; RR-120N: Rice residue Removed with 120 kg N ha^{-1}; RI- Rice residue Incorporated with 120 kg N ha^{-1}; GM – Green Manure; FYM – Farmyard Manure; WS: Wheat Straw.

Table 2. Soil and climatic characteristics of the various sites used in the study.

Site	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.

Table 3. Parameter values of Yang's model (Yang, 1996).

Substrate	R_9	S
Soil organic matter	0.057	0.46
Farm yard manure	0.82	0.49
Green manure	1.39	0.64
Straw	1.11	0.66
Roots	0.80	0.67
Rhizodeposition*	1.50	0.70

* Parameters not originally present in Yang's model were calibrated.

The relative decomposition rate for a given organic substrate has been shown to decrease with time (Kolenbrander, 1969; Sauerbeck and Gonzalez, 1977). Janssen (1984) developed an equation to describe the relationship between the actual relative decomposition rate, k, and time, t, which can be used for all types of organic materials. In practice, however, it is easier to derive equations for the relation between the *average relative decomposition rate* since the beginning of the decomposition (K), and time (Kolenbrander, 1969; Yang, 1996). Yang calculated K from:

$$K = \frac{1}{t} \ln\left(\frac{Y_0}{Y_t}\right) \qquad (2)$$

where, Y_0 and Y_t are the SOC contents at times 0 and t, respectively.
He found a negative linear relationship between ln(K) and ln(t) for all organic substrates he studied, including glucose, plant materials, peat and soil organic matter:

$$\ln(K) = \ln(R) - S \ln(t) \qquad (3a) \text{ or}$$
$$K = R\, t^{-S} \qquad (3b)$$

where, R and S are regression constants, with $K = R$ when $t = 1$ and hence, R is the average relative decomposition rate over the time interval 0-1. The slope of ln(K) versus ln(t) is equal to minus S. The negative sign indicates that K decreases with time. Substituting k in Eqn. 1 by Eqn. 3b yields:

$$Y_t = Y_0 e^{(-R\, t^{1-S})} \qquad (4)$$

The value of K depends on temperature, but the value of S does not (Yang and Janssen, 2000). Yang introduced the concept of R_9, the value of K at a temperature of

9 °C. Table 3 gives average values of R_9 and S, derived by Yang for major organic materials used in agriculture. The values for rhizodeposition were estimated 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-values also have high S-values (Yang, 1996), both values are higher for rhizodeposition than for green manure (Table 3).

Yang took the effect of temperature into consideration by introducing a correction factor (*f*) in Eqn. 4:

$$Y_t = Y_0 e^{(-R_9 (ft)^{1-S})} \qquad (5)$$

The temperature correction factor, *f*, modifies the time component in the equation; the product *f* t is comparable to *physiological time*, as a fixed heat sum is required to decompose a unit of SOC. In our study, the value of *f* was calculated using the mean annual temperature at the site. Following Noij et al. (1993) and Yang (1996), we calculated *f* as:

$$F = 2^{(T-9)/9}$$

for the temperature range between 9 and 27 °C.

Hence, one year of decomposition at 27 °C is equivalent to two years of decomposition at 18 °C or four years at 9 °C (Jenkinson and Ayanaba, 1977).

Organic carbon inputs

In cropping systems, organic matter input into the soil depends on crop biomass produced and the fraction that is incorporated into the soil in the form of roots, root exudates, and crop residues. Since the general practice in IGP is to remove the straw after grain harvest for use as forage, fuel, or building material, root biomass and rhizodeposition are the major soil carbon sources. In most of the long-term experiments reported in Table 1, straw was removed from the field during or after harvest. We calculated carbon addition through roots from total aboveground biomass by multiplying the root-shoot ratio (Eqn. 7) (Bronson et al., 1998; Kogel-Knabner, 2002) with the total aboveground biomass, which in turn was found as the quotient of grain yield and harvest index (HI; Table 4). For rice and wheat, a HI value of 0.4 was used (Sidhu and Beri, 1989; Thakur et al., 1995; Khan et al., 2006). Harvest index for jute was set to 0.25 (Kundu et al., 1959; Palit and Bhattacharya, 1982; Johansen et al.,

Table 4. Coefficients used to calculate the carbon input into the soil from various sources of carbon.

Coefficients	Rice	Wheat	Pulses	Jute	GM	FYM
Harvest Index	0.4	0.4	1.0	0.25	-	-
Root: shoot ratio	0.1	0.1	0.1	0.1	-	-
Fraction of carbon in root biomass (kg C/ kg of root)	0.4	0.4	0.4	0.4	-	-
Fraction of carbon in straw biomass (kg C/ kg of straw)	0.4	0.4	0.4	0.4	-	-
Rhizodeposition/shoot biomass	0.15	0.15	0.15	0.15	-	-
Carbon/ Rhizodeposition (kg C/kg of rhizodeposition)	0.35	0.35	0.35	0.35	-	-
Carbon/ GM biomass (kg C/ kg of GM)	-	-	-	-	0.44	-
Carbon/ FYM biomass (kg C/ kg of FYM)	-	-	-	-	-	0.38

GM- Green manure; FYM- Farmyard manure

1985). For cowpea, used as fodder, total aboveground biomass represents yield and therefore, HI was set to one.

Root mass was calculated from total aboveground biomass for a soil depth of 15 cm, using root-shoot ratios of 0.1 for rice, wheat, jute and cowpea (Table 4; Yoshida, 1981; Gajri and Prihar, 1985; Palit, 1985; Haverman, 1986; Wisserhof, 1995; Terao et al., 1997). These values are amenable to modification with more exact values available for each site. Rhizodeposition of carbon during crop growth was found to be 5-20% of total aboveground biomass in a greenhouse study with different species (Shamoot et al., 1968) and 20% of total carbon assimilation for wheat (Sauerbeck and Johnen, 1977). Keith et al. (1986), using ^{14}C, found a rhizodeposition during the growing season of wheat of 30% of total aboveground carbon accumulation. Bronson et al. (1998) used a value of 15% of total shoot biomass as rhizodeposition to calculate the carbon balance for a rice-based cropping system in South Asia, a value that we also adopted. Annual carbon input into a soil [2], y (kg ha^{-1}) from different sources, i.e. rhizodeposition, roots, straw from different crops, green manure (GM) and/or farmyard manure (FYM), in a cropping system is calculated as:

$$y_{i,j} = B_{i,j}\, C_{i,j} \qquad (6)$$

---

[2] y refers to added organic carbon and Y refers to indigenous soil carbon

where $y_{i,j}$ is carbon input (kg ha^{-1}) during the cultivation of the i^{th} crop (rice, wheat, cowpea and jute) through the j^{th} source (roots, rhizodeposition, straw, GM or FYM), $B_{i,j}$ and $C_{i,j}$ are the dry weights (kg ha^{-1}) and carbon fractions (kg C kg^{-1} dry weight; Table 4) of the various sources.

For each crop (i), inputs (kg dry weight ha^{-1}) through roots ($B_{i,roots}$) and rhizodeposition ($B_{i,rhiz}$) are calculated from total aboveground biomass.

$$B_{i,roots} = (x_i/\mu_i)\, P_{i,roots} \tag{7}$$

$$B_{i,rhiz} = (x_i/\mu_i)\, P_{i,rhizo} \tag{8}$$

where x_i and μ_i are the yield and harvest index of the i^{th} crop, respectively, and $P_{i,roots}$ and $P_{i,rhizo}$ the weight proportions of roots and excreted rhizodeposition, respectively, to total aboveground biomass at harvest.

Total carbon input per crop rotation is the sum of the contributions from the various sources:

$$y_{total} = \sum_{i=1}^{n}\sum_{j=1}^{m} y_{i,j} \tag{9}$$

In principle, added carbon components are gradually converted. A part leaves the soil as CO_2, while the other transformation products and the remnants of the original components become part of SOC. Since it is difficult to quantify the proportion of added organic matter that changes into SOC, in this study, we followed each added organic material and the indigenous SOC separately. Total soil carbon at time t, Yn_t (Mg ha^{-1}), is the sum of remaining indigenous soil organic carbon at time t, Y_t, and the remaining carbon of the additions through crop residues, GM and FYM, y_t. So,

$$Yn_t = Y_t + y_t \tag{10}$$

Net soil carbon change during the period Δt, ΔYn_t, equals:

$$\Delta Yn_t = \Delta Y_t + \Delta y_t \tag{11}$$

where ΔY_t represents the reduction in soil organic carbon through decomposition, and Δy_t, net carbon addition through crop inputs, GM and FYM.

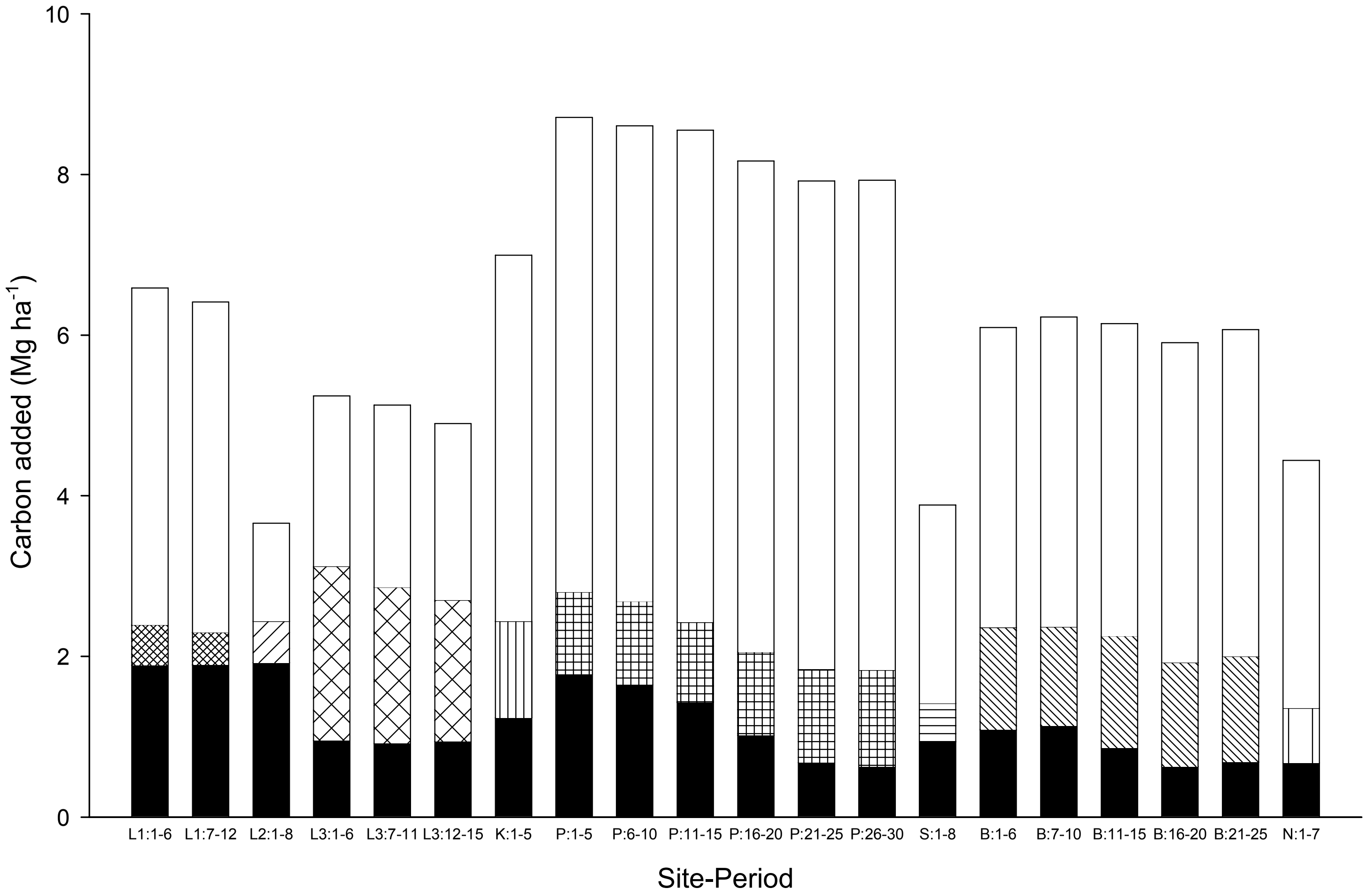

Figure 1. Average annual carbon input into the soil (kg ha^{-1}) under different treatments during different periods of cropping at various locations in the IGP (Note: X-axis indicates the site and period of cropping (years), e.g.: L1:1-6 means, site Ludhiana1 and period 1-6 years (see Table 1 for details of treatments); black bars at the bottom correspond to treatment 1, white bars at the top correspond to treatment 3 and the middle shaded bars correspond to treatment 2; for all the treatments, values on Y-axis start from zero).

Results and discussion

Organic carbon inputs

In soils grown to cereals, the annual rate of carbon addition is the single most important factor determining soil organic matter content (Rasmussen et al., 1980). It is of the order of 1-2 Mg ha^{-1} (Jenkinson and Rayner, 1977; Jenkinson et al., 1992). In the experiments reviewed in this study, average annual carbon additions without organic amendments fall in the range of 1.4 to 3.2 Mg ha^{-1} (Figure 1; Treatment-2). Fifty to sixty percent of the carbon added consists of rhizodeposition and the remainder is root residues.

Model evaluation: soil organic carbon

Calculated[3] and observed soil organic carbon contents (g kg^{-1}) for the surface 0-15 cm depth for different sites under different treatments are given in Figures 2 and 3. Calculated soil organic carbon contents for Ludhiana-1 show satisfactory agreement with the observed values for the different treatments (Figure 2). Soil organic carbon content increases over time in all treatments similar to the observations, except for the control. Soil organic carbon content in Ludhiana-2 also follows the observed trend. However, for the Residue Incorporated (RI-120N) and control treatments, the model slightly underestimates carbon contents, with no clear difference between the observed values of RR-120N and the control. In Ludhiana-3, the model underestimates SOC content in all three treatments (Figure 2). A high soil pH (8.2) at this site may be a reason for the slow decomposition of SOC, as microbial activity is suppressed at high pH.

Contrary to Ludhiana, observed soil organic carbon in Karnal decreases in the chemical fertilizer treatment, despite a comparable initial organic carbon level (Table 2) and comparable biomass input (Figure 1). This difference in carbon dynamics in Karnal soils is most likely associated with soil sodicity. Therefore, calculated SOC values are overestimated for all three treatments in Karnal, as the effect of sodicity is not incorporated in the model. The effect is more chemical than biological; though sodicity may hamper microbial activity, mineralization of organic matter is found to increase, as a result of chemical hydrolysis, which dissolves SOC and makes it more accessible to the microbes (Laura, 1973; 1976; Chander et al., 1994; Wong et al., 2004).

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[3] Hereafter, calculated refers to model results

In Pantnagar, in the Upper Gangetic Plains, with a virgin soil at the start of the experiment, SOC dynamics in the three treatments (Figure 3) were inconsistent (Katyal, 2001). In the control and 100% NPK treatments, SOC was maintained or slightly increased for the first 5-8 years, and was higher than that with FYM application. The reason for this relatively stable SOC-content apparently is the addition of organic matter-rich topsoil by erosion from the upper slopes (Gaur and Singh, 1982; Katyal, 2001). Over the period 5-15 years of cultivation, SOC drastically declined to 50 and 65 percent of their initial value in the control and 100% NPK treatments, respectively. Intensive cultivation over these years by puddling and tillage may have destroyed soil aggregates formed in this virgin soil, resulting in a rapid decline in SOC through faster aggregate turnover (Ram, 1998; Six et al., 2004). After 15 years of cropping, the rate of decrease in SOC declines, as if SOC is reaching an equilibrium level, as suggested by Buyanovsky and Wagner (1998). However, the model predicts a consistent decrease, since it does not take into account external factors like soil addition or erosion. The rate of decline of SOC in the field is so high that, at the end of 30 years, the observed value in the control treatment was only one-third of the initial SOC, while the calculated value was almost double. For the 100% NPK treatment, these figures are 57 and 66 percent, respectively. In the NPK+FYM treatment, there is a marginal increase in SOC after 30 years of cropping (from 14.8 to 15.6 g kg^{-1}). The model predicts an initial increase in SOC with FYM application, followed by a decline to a value of 13.2 g kg^{-1} after 30 years.

In Samastipur, in the MGP region, characterized by a higher mean annual temperature (26 °C) and calcareous soils, SOC shows an increase after 8 years of cultivation in all treatments, while the model predicts a slight decline (Figure 3). The low carbon input (1.0- 4.0 Mg ha^{-1}) at this site leads to a decline in SOC in the model calculation, whereas, in reality, the high $CaCO_3$ content of the soil may have played a role through its protective effect on SOC (Prasad and Sinha, 2000; Six et al., 2004).

In Barrackpore, SOC declines in all three treatments for the first 6 years; subsequently, it stabilizes, except in the treatment with FYM addition, where it increases. The model also shows a decline for all three treatments, but less pronounced. After 6 years, observed values of SOC reach an equilibrium, whereas the model predicts a continuous decline. After a 25-year cultivation period, calculated SOC values (5.2, 4.5, 4.0 g kg^{-1}, for Treatment-1, Treatment-2 and Treatment-3, respectively) are very close to the observed values (4.5, 4.3 and 4.0 g kg^{-1}) for all the treatments. However, recent reports (Manna et al., 2006, data not included in this study) show an increase in

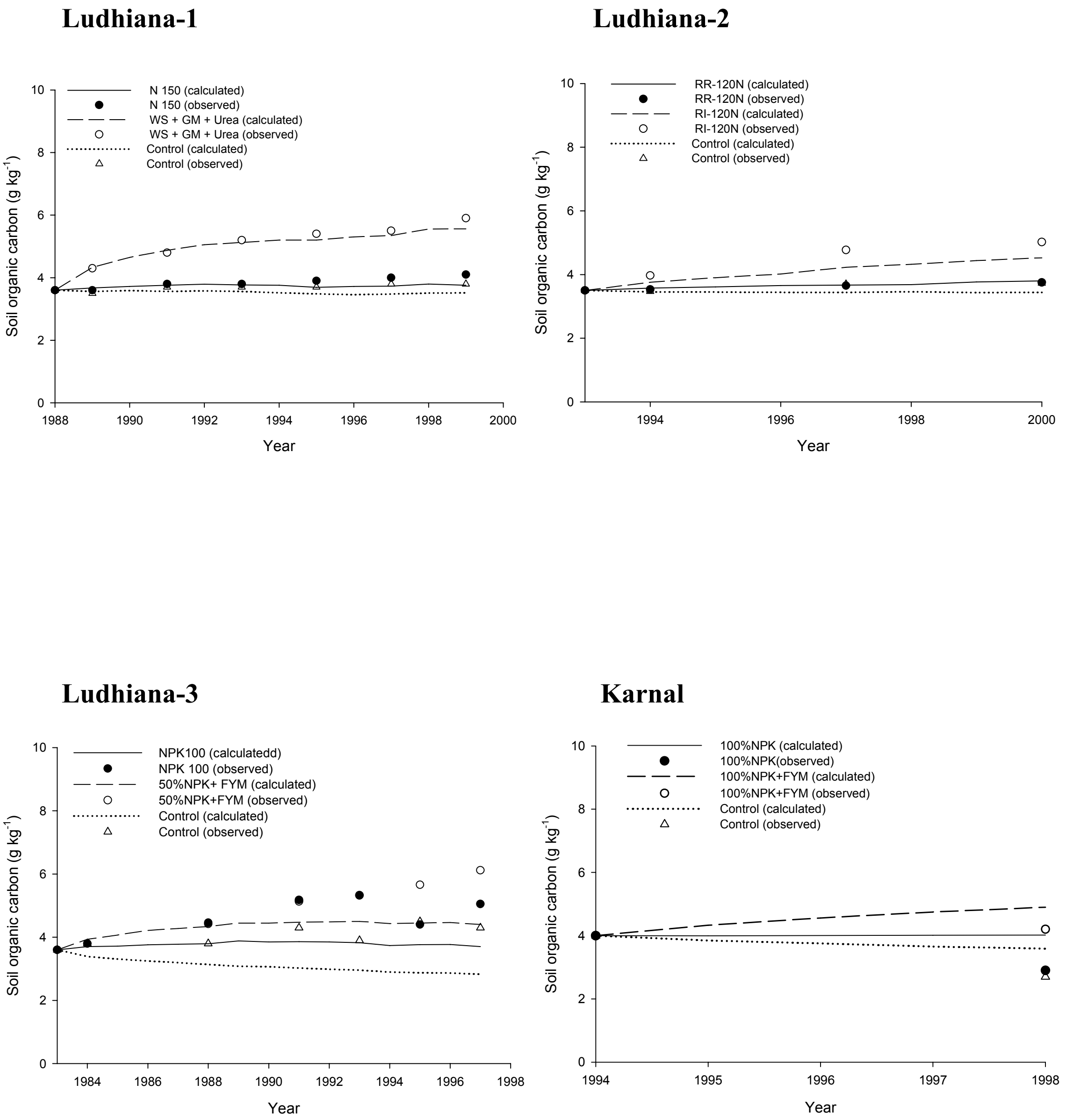

Figure 2. Observed and calculated values of soil organic carbon for various sites in the Trans-Gangetic Plain.

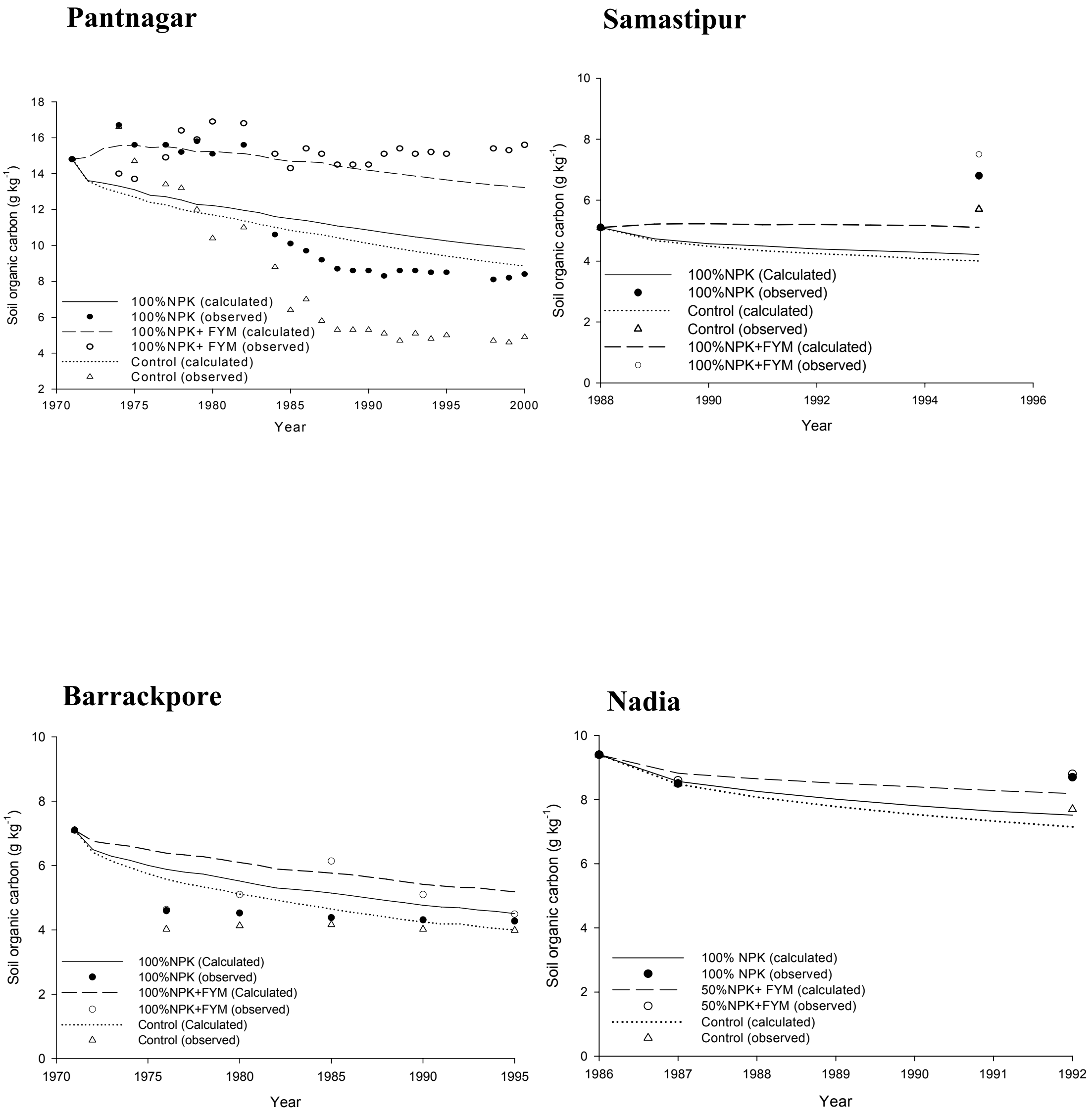

Figure 3. Observed and calculated values of soil organic carbon for sites in the Upper- (Pantnagar), Middle- (Samastipur) and Lower- (Barrackpore and Nadia) Gangetic Plains.

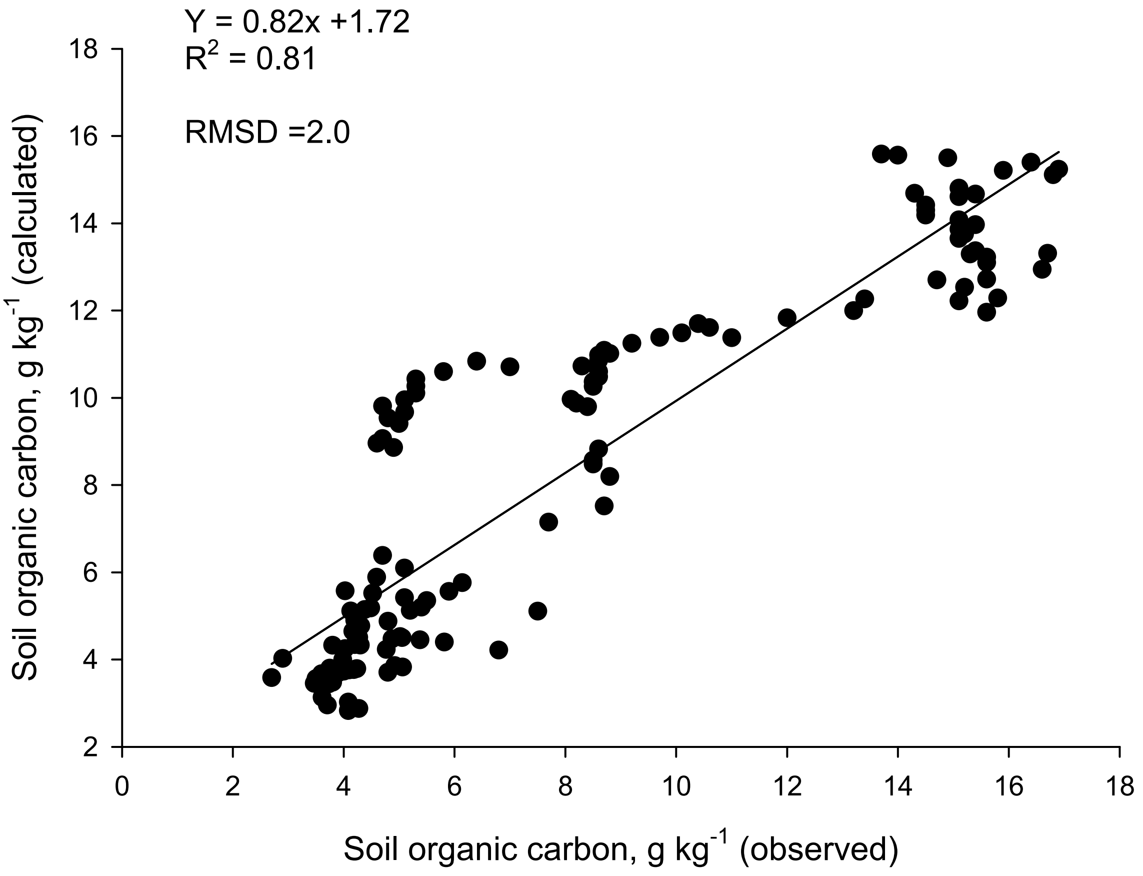

Figure 4. Observed and calculated values of soil organic carbon for the whole dataset.

SOC after 30 years under Treatment-1 (7.9 g kg^{-1}), Treatment-2 (7.4 g kg^{-1}) and Treatment-3 (5.1 g kg^{-1}), without any substantial increase in yield.

In Nadia, SOC declines in all treatments during the 7 years of cultivation. The model also predicts a decline in SOC in all three treatments. A low carbon input (Figure 1) into the soil, as a result of low biomass production, may be the reason for this decline, even with FYM application.

Observed and calculated values of SOC (Figure 4) show a strong correlation (R^2= 0.81), with a RMSD[4] of 2.0 g kg^{-1}, i.e. 25 percent of the mean observed values.

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[4] RMSD $= \left[\frac{\sum_{i=1}^{n} (Yi-Oi)^2}{n} \right]^{0.5}$ where Y_i and O_i are simulated and observed values, respectively.

Table 5. Periodic carbon balances at various sites under rice-based cropping systems in the IGP.

	Period (years)													
	Ludhiana-1				Ludhiana-2		Ludhiana-3						Karnal	
	1-6		7-12		1-8		1-6		7-11		12-15		1-5	
	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}
Treatment-1														
Yn_t, initial (Obs.)	8.4	3.6	12.1	5.2	8.1	3.5	8.4	3.6	9.7	4.2	11.7	5.0	9.3	4.0
Yn_t, final (Obs.)	12.1	5.2	13.7	5.9	11.7	5.0	9.7	4.2	11.7	5.0	13.5	5.8	9.8	4.2
ΔYn_t (Obs.)	3.7	1.6	1.6	0.7	3.5	1.5	1.4	0.6	2.0	0.9	1.8	0.8	0.5	0.2
Yn_t, initial*	8.4	3.6	11.9	5.1	8.1	3.5	8.4	3.6	10.1	4.3	10.5	4.5	9.3	4.0
ΔY_t (Cal.)	-1.7	-0.7	-0.8	-0.3	-2.0	-0.9	-1.7	-0.7	-0.7	-0.3	-0.4	-0.2	-1.8	-0.8
Δy_t (Cal.)	5.3	2.3	1.8	0.8	4.4	1.9	3.5	1.5	1.0	0.4	0.2	0.1	3.9	1.7
ΔYn_t (Cal.)	3.5	1.5	1.0	0.4	2.4	1.0	1.7	0.7	0.4	0.2	-0.2	-0.1	2.1	0.9
Yn_t, final (Cal.)	11.9	5.1	12.9	5.6	10.5	4.5	10.1	4.3	10.5	4.5	10.2	4.4	11.4	4.9
Treatment-2														
Yn_t, initial (Obs.)	8.4	3.6	8.8	3.8	8.1	3.5	8.4	3.6	9.8	4.2	11.7	5.1	9.3	4.0
Yn_t, final (Obs.)	8.8	3.8	9.5	4.1	8.7	3.8	9.8	4.2	11.7	5.1	11.1	4.8	6.7	2.9
ΔYn_t (Obs.)	0.5	0.2	0.7	0.3	0.6	0.3	1.5	0.6	1.9	0.8	-0.6	-0.3	-2.6	-1.1
Yn_t, initial*	8.4	3.6	8.8	3.8	8.1	3.5	8.4	3.6	8.8	3.8	8.9	3.8	9.3	4.0
ΔY_t (Cal.)	-1.7	-0.7	-0.8	-0.3	-2.0	-0.9	-1.7	-0.7	-0.7	-0.3	-0.4	-0.2	-1.8	-0.8
Δy_t (Cal.)	2.1	0.9	0.8	0.3	2.7	1.2	2.2	0.9	0.8	0.3	0.1	0.0	1.9	0.8
ΔYn_t (Cal.)	0.4	0.2	0.0	0.0	0.7	0.3	0.4	0.2	0.1	0.0	-0.3	-0.1	0.0	0.0
Yn_t, final (Cal.)	8.8	3.8	8.7	3.8	8.8	3.8	8.8	3.8	8.9	3.8	8.6	3.7	9.3	4.0
Treatment-3														
Yn_t, initial (Obs.)	8.4	3.6	8.6	3.7	8.1	3.5	8.4	3.6	8.4	3.6	8.6	3.7	9.3	4.0
Yn_t, final (Obs.)	8.6	3.7	8.8	3.8	8.7	3.7	8.4	3.6	8.6	3.7	9.5	4.1	6.3	2.7
ΔYn_t (Obs.)	0.2	0.1	0.2	0.1	0.5	0.2	0.0	0.0	0.2	0.1	0.9	0.4	-3.0	-1.3
Yn_t, initial*	8.4	3.6	8.3	3.6	8.1	3.5	8.4	3.6	7.3	3.1	6.9	3.0	9.3	4.0
ΔY_t (Cal.)	-1.7	-0.7	-0.8	-0.3	-2.0	-0.9	-1.7	-0.7	-0.7	-0.3	-0.4	-0.2	-1.8	-0.8
Δy_t (Cal.)	1.6	0.7	0.7	0.3	1.8	0.8	0.7	0.3	0.3	0.1	0.1	0.0	0.8	0.4
ΔYn_t (Cal.)	-0.1	0.0	-0.1	0.0	-0.1	-0.1	-1.1	-0.5	-0.4	-0.2	-0.3	-0.1	-1.0	-0.4
Yn_t, final (Cal.)	8.3	3.6	8.2	3.5	8.0	3.4	7.3	3.1	6.9	3.0	6.6	2.8	8.3	3.6

continued…

	Pantnagar												Samastipur	
	1-5		6-10		11-15		16-20		21-25		26-30		1-8	
	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}
Treatment-1														
Yn_t, initial (Obs.)	29.3	14.8	27.1	13.7	33.5	16.9	28.3	14.3	28.7	14.5	29.9	15.1	11.5	5.1
Yn_t, final (Obs.)	27.1	13.7	33.5	16.9	28.3	14.3	28.7	14.5	29.9	15.1	30.9	15.6	16.9	7.5
ΔYn_t (Obs.)	-2.2	-1.1	6.3	3.2	-5.1	-2.6	0.4	0.2	1.2	0.6	1.0	0.5	5.4	2.4
Yn_t, initial*	29.3	14.8	30.9	15.6	30.2	15.2	29.1	14.7	28.1	14.2	27.0	13.6	11.5	5.1
ΔY_t (Cal.)	-5.5	-2.8	-2.6	-1.3	-1.8	-0.9	-1.4	-0.7	-1.1	-0.6	-1.0	-0.5	-3.2	-1.4
Δy_t (Cal.)	7.0	3.5	1.9	0.9	0.7	0.3	0.4	0.2	0.1	0.0	0.1	0.1	3.2	1.4
ΔYn_t (Cal.)	1.6	0.8	-0.7	-0.3	-1.1	-0.6	-1.0	-0.5	-1.1	-0.5	-0.9	-0.4	0.0	0.0
Yn_t, final (Cal.)	30.9	15.6	30.2	15.2	29.1	14.7	28.1	14.2	27.0	13.6	26.2	13.2	11.5	5.1
Treatment-2														
Yn_t, initial (Obs.)	29.3	14.8	30.9	15.6	29.9	15.1	20.0	10.1	17.0	8.6	16.8	8.5	11.5	5.1
Yn_t, final (Obs.)	30.9	15.6	29.9	15.1	20.0	10.1	17.0	8.6	16.8	8.5	16.6	8.4	15.3	6.8
ΔYn_t (Obs.)	1.6	0.8	-1.0	-0.5	-9.9	-5.0	-3.0	-1.5	-0.2	-0.1	-0.2	-0.1	3.8	1.7
Yn_t, initial*	29.3	14.8	25.9	13.1	24.2	12.2	22.7	11.5	21.5	10.9	20.3	10.3	11.5	5.1
ΔY_t (Cal.)	-5.5	-2.8	-2.6	-1.3	-1.8	-0.9	-1.4	-0.7	-1.1	-0.6	-1.0	-0.5	-3.2	-1.4
Δy_t (Cal.)	2.1	1.1	0.8	0.4	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	1.2	0.5
ΔYn_t (Cal.)	-3.4	-1.7	-1.7	-0.9	-1.5	-0.7	-1.3	-0.6	-1.2	-0.6	-0.9	-0.5	-2.0	-0.9
Yn_t, final (Cal.)	25.9	13.1	24.2	12.2	22.7	11.5	21.5	10.9	20.3	10.3	19.4	9.8	9.5	4.2
Treatment-3														
Yn_t, initial (Obs.)	29.3	14.8	29.1	14.7	20.6	10.4	12.7	6.4	10.5	5.3	9.9	5.0	11.5	5.1
Yn_t, final (Obs.)	29.1	14.7	20.6	10.4	12.7	6.4	10.5	5.3	9.9	5.0	9.7	4.9	12.8	5.7
ΔYn_t (Obs.)	-0.2	-0.1	-8.5	-4.3	-7.9	-4.0	-2.2	-1.1	-0.6	-0.3	-0.2	-0.1	1.4	0.6
Yn_t, initial*	29.3	14.8	25.1	12.7	23.2	11.7	21.4	10.8	20.0	10.1	18.6	9.4	11.5	5.1
ΔY_t (Cal.)	-5.5	-2.8	-2.6	-1.3	-1.8	-0.9	-1.4	-0.7	-1.1	-0.6	-1.0	-0.5	-3.2	-1.4
Δy_t (Cal.)	1.3	0.7	0.6	0.3	0.1	0.0	-0.1	0.0	-0.2	-0.1	-0.1	-0.1	0.8	0.3
ΔYn_t (Cal.)	-4.2	-2.1	-2.0	-1.0	-1.7	-0.9	-1.4	-0.7	-1.4	-0.7	-1.1	-0.6	-2.5	-1.1
Yn_t, final (Cal.)	25.1	12.7	23.2	11.7	21.4	10.8	20.0	10.1	18.6	9.4	17.5	8.9	9.0	4.0

continued…

	Barrackpore										Nadia	
	1-6		7-10		11-15		16-20		21-25		1-7	
	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}
Treatment-1												
Yn_t, initial (Obs.)	20.3	7.1	13.4	4.7	14.6	5.1	17.6	6.1	14.6	5.1	18.3	9.4
Yn_t, final (Obs.)	13.4	4.7	14.6	5.1	17.6	6.1	14.6	5.1	12.8	4.5	17.2	8.8
ΔYn_t (Obs.)	-6.9	-2.4	1.1	0.4	3.0	1.0	-3.0	-1.0	-1.7	-0.6	-1.2	-0.7
Yn_t, initial*	20.3	7.1	18.3	6.4	17.4	6.1	16.5	5.8	15.5	5.4	18.3	9.4
ΔY_t (Cal.)	-5.1	-1.8	-1.6	-0.5	-1.4	-0.5	-1.1	-0.4	-0.9	-0.3	-4.8	-2.5
Δy_t (Cal.)	3.0	1.1	0.7	0.3	0.4	0.2	0.1	0.0	0.2	0.1	2.4	1.3
ΔYn_t (Cal.)	-2.1	-0.7	-0.8	-0.3	-1.0	-0.3	-1.0	-0.3	-0.7	-0.2	-2.4	-1.2
Yn_t, final (Cal.)	18.3	6.4	17.4	6.1	16.5	5.8	15.5	5.4	14.8	5.2	16.0	8.2
Treatment-2												
Yn_t, initial (Obs.)	20.3	7.1	13.1	4.6	12.9	4.5	12.5	4.4	12.3	4.3	18.3	9.4
Yn_t, final (Obs.)	13.1	4.6	12.9	4.5	12.5	4.4	12.3	4.3	12.2	4.3	17.0	8.7
ΔYn_t (Obs.)	-7.2	-2.5	-0.2	-0.1	-0.4	-0.1	-0.2	-0.1	-0.1	0.0	-1.4	-0.7
Yn_t, initial*	20.3	7.1	16.8	5.9	15.8	5.5	14.7	5.1	13.6	4.8	18.3	9.4
ΔY_t (Cal.)	-5.1	-1.8	-1.6	-0.5	-1.4	-0.5	-1.1	-0.4	-0.9	-0.3	-4.8	-2.5
Δy_t (Cal.)	1.6	0.6	0.5	0.2	0.3	0.1	0.0	0.0	0.1	0.0	1.1	0.6
ΔYn_t (Cal.)	-3.5	-1.2	-1.0	-0.4	-1.1	-0.4	-1.1	-0.4	-0.7	-0.3	-3.7	-1.9
Yn_t, final (Cal.)	16.8	5.9	15.8	5.5	14.7	5.1	13.6	4.8	12.9	4.5	14.7	7.5
Treatment-3												
Yn_t, initial (Obs.)	20.3	7.1	11.5	4.0	11.8	4.1	11.9	4.2	11.4	4.0	18.3	9.4
Yn_t, final (Obs.)	11.5	4.0	11.8	4.1	11.9	4.2	11.5	4.0	11.4	4.0	15.0	7.7
ΔYn_t (Obs.)	-8.8	-3.1	0.3	0.1	0.1	0.0	-0.4	-0.1	-0.1	0.0	-3.3	-1.7
Yn_t, initial*	20.3	7.1	15.9	5.6	14.6	5.1	13.3	4.6	12.1	4.2	18.3	9.4
ΔY_t (Cal.)	-5.1	-1.8	-1.6	-0.5	-1.4	-0.5	-1.1	-0.4	-0.9	-0.3	-4.8	-2.5
Δy_t (Cal.)	0.7	0.2	0.2	0.1	0.1	0.0	-0.1	0.0	0.1	0.1	0.4	0.2
ΔYn_t (Cal.)	-4.4	-1.5	-1.3	-0.5	-1.3	-0.5	-1.1	-0.4	-0.7	-0.2	-4.4	-2.3
Yn_t, final (Cal.)	15.9	5.6	14.6	5.1	13.3	4.6	12.1	4.2	11.4	4.0	13.9	7.1

Yn_t, initial: initial amount of SOC; Yn_t, final: final amount of SOC at the end of cropping period; ΔYn_t: net change in SOC; ΔY_t: SOC decomposed; Δy_t: effective amount of organic carbon added.

* Initial carbon content calculated by the model equals the final value from the preceding period, at the start of each period. At the start of the first period, it is equal to the observed initial carbon.

Carbon balance

Table 5 shows observed and calculated net carbon balances for the different cropping periods. For Ludhiana-1, in Treatment-1 (GM+straw+52 kg N ha^{-1}), the observed net carbon balance is positive for the first 6-year period of cropping (ΔYn_t; 3.7 Mg ha^{-1}). According to the model calculations, 1.7 Mg C ha^{-1} disappears through SOC decomposition (ΔY_t) and at a net (after decomposition) addition of 5.3 Mg ha^{-1} (Δy_t) through carbon input, results in a positive carbon balance (ΔYn_t) of 3.5 Mg ha^{-1}. The calculated net carbon balance for the 7-12 year period is similarly positive (1.0 Mg ha^{-1}), with 0.8 Mg ha^{-1} lost in association with SOC decomposition and a net contribution from carbon inputs of 1.8 Mg ha^{-1}, although it is lower than the observed increase (1.6 Mg ha^{-1}). In Treatment-2 (150 kg N ha^{-1}), a net carbon addition of 2.1 Mg ha^{-1} (Δy_t) results in a positive carbon balance (0.4 Mg ha^{-1}) after the first 6 years of cropping, comparable to the observed value (0.5 Mg ha^{-1}). The observed net carbon balance is similarly positive for the 7-12 year period (0.7 Mg ha^{-1}), whereas the calculated balance is zero. In the control treatment, the calculated carbon balances are negative (-0.1 Mg ha^{-1}) for both periods, whereas the observed values are slightly positive (0.2 Mg ha^{-1}).

For Ludhiana-2, after 8 years of cultivation, calculated carbon balances are 2.4, 0.7 and -0.1 Mg ha^{-1} compared to observed values of 3.5, 0.6 and 0.5 for treatments RI-120N (Treatment-1), RR-120N (Treatment-2), and RR-0N (Treatment-3), respectively. For Ludhiana-3, observed carbon balances for the periods of 1-6 and 7-11 years of cultivation are positive and increasing (1.5 and 1.9 Mg ha^{-1}) under Treatment-2 (100% NPK), compared to calculated values of 0.4 and 0.1 Mg ha^{-1}. During the 12-15 year period, both, observed (-0.6 Mg ha^{-1}) and calculated (-0.3 Mg ha^{-1}) carbon balances are negative. With FYM application (Treatment-1), observed and calculated carbon balances are positive for all three periods, except for the calculated balance during the 12-15 year period. In the control (Treatment-3), the observed carbon balance is unexpectedly positive for relatively lower carbon input (Figure 1) than at the other sites in Ludhiana, and is increasing, i.e. 0, 0.2 and 0.9 Mg ha^{-1} over the 1-6, 7-11 and 12-15 year cropping period, respectively, compared to negative values (-1.1, -0.4, and -0.3 Mg ha^{-1}) for the calculated balances.

For Karnal, the model overestimates SOC, since the effect of soil sodicity on SOC dynamics is not taken into account. In Treatment-1 (100% NPK+ FYM), both calculated and observed carbon balances are positive after 5 years of cultivation, however, with a higher value in the model (2.1 Mg ha^{-1}) than observed (0.5 Mg ha^{-1}). For Treatment-2 (100% NPK), the observed carbon balance is negative (-2.6 Mg ha^{-1}), compared to a zero balance in the model. In the control (Treatment-3), however, both observed (-3.0 Mg ha^{-1}) and calculated (-1.0 Mg ha^{-1}) carbon balances are negative.

In Pantnagar, during the first 5-year period of cropping, observed carbon balances are positive for Treatment-2 (100% NPK; 1.6 Mg C ha^{-1}) and negative for Treatment-1 (100% NPK+ FYM; -2.2 Mg ha^{-1}) and Treatment-3 (Control; -0.2 Mg ha^{-1}). The high negative carbon balance in Treatment-1, even with a relatively high annual carbon input of about 9 Mg ha^{-1} (Figure 1) and a positive carbon balance for Treatment-2 (with annual carbon input of 2.8 Mg ha^{-1}), shows some kind of inconsistency in the system. The disparity may be due to some kind of external forces like erosion (Katyal et al., 2001) or due to an analytical error. For the period of 6-10 years, the control treatment showed a maximum (-8.5 Mg ha^{-1}) and Treatment-2 a marginal (-1.0 Mg ha^{-1}) loss of carbon, whereas in Treatment-1, the carbon balance was strongly positive (6.3 Mg ha^{-1}). The trend of high negative carbon balances continued in the 11-15 year period in all three treatments. In Treatment-2, the carbon balance was remarkably negative (-9.9 Mg ha^{-1}, 10 times higher than during the second period), resulting in loss of one-third of the total carbon. Treatment-1 also showed a considerable decline (-5.1 Mg ha^{-1}) during this period. The reason for these high rates of decline is not clear. In the subsequent periods of 16-20, 21-25 and 26-30 years cultivation, observed carbon balances tended towards an equilibrium with carbon inputs. In Treatment-1, SOC slightly and steadily increased, to attain a new higher equilibrium, whereas in Treatment-2 it decreased slightly towards a lower equilibrium. In the control treatment, the relatively lower carbon input resulted in a still lower equilibrium SOC level. The model calculates negative balances for all three treatments and all periods, except for the first 5 years in Treatment-1, with the highest values during the first five years in Treatment-2 and Treatment-3.

Eight years of cultivation in the calcareous soils of Samastipur showed a positive carbon balance in Treatment-2 (100% NPK; 3.8 Mg ha^{-1}) compared to a negative value in the model (-2.0 Mg ha^{-1}). In Treatment-1, the calculated loss of carbon through decomposition of indigenous SOC is compensated by FYM additions and resulted in maintenance of the SOC-level, whereas the observations showed a high positive carbon balance (5.4 Mg ha^{-1}). Similarly, in the control treatment the calculated balance was negative (-2.5 Mg ha^{-1}), compared to an observed positive balance (1.4 Mg ha^{-1}). The protective effect of $CaCO_3$ in this soil on SOC may be the reason for the observed lower rate of carbon turnover.

As in Pantnagar, the experiment in Barrackpore started on a virgin soil in 1969 with rice as the first crop (Manna et al., 2006). Consequently, in the first 6-year period, the observed carbon balances were strongly negative in all three treatments, i.e. -6.9, -7.2 and -8.8 Mg ha^{-1} in Treatment-1 (100% NPK + FYM), Treatment-2 (100% NPK) and Treatment-3 (Control), respectively. Increasing intensity of cultivation with alternate wetting and drying, puddling, and tillage operations (Manna et al., 2006), with repeated applications of inorganic fertilizers causes rapid disintegration of aggregates and decomposition of the associated SOC (Tisdall and Oades, 1982; Manna et al., 2006). The model results also show a decline (-2.1, -3.5, and -4.4 Mg C ha^{-1} for Treatment-1, Treatment-2 and Treatment-3, respectively) over the corresponding period, but of lower magnitude. Over the subsequent cropping periods of 7-10, 11-15, 16-20 and 21-25 year, observations show an equilibrium situation for Treatment-2 and Treatment-3. In Treatment-1, carbon level increases during the 7-10 and 11-15 year periods, but subsequently decreases to a value similar to that in Treatment-2. The reason for such a decline in the last two periods is not clear. Calculated carbon balances for the corresponding periods of 7-10, 11-15, 16-20 and 21-25 years, are consistently negative in all three treatments, with values decreasing over time towards an equilibrium at a lower carbon level.

In Nadia, seven years of cultivation under Treatment-1 (50% NPK + FYM), Treatment-2 (100% NPK), and Treatment-3 (Control) all result in negative carbon balances of -1.2, -1.4, and -3.3 Mg ha^{-1}, while the model overestimates the losses, i.e. -2.4, -3.7 and -4.4 Mg ha^{-1}, respectively.

Sensitivity analysis

Quantity and quality of the organic substrates added and prevailing environmental conditions determine organic carbon dynamics in soil. Less degradable substrates (roots and FYM) will result in higher accumulation per unit of carbon input than those with higher degradability (rhizodeposition and GM). Sensitivity of calculated organic carbon contents in soil to different environmental (temperature) and model parameters (R and S) and to variations in crop yield and organic substrate input is illustrated in Figures 5, 6 and 7. A change in ambient temperature (± 3 °C, in relation to a base temperature of 24 °C, the average of the mean annual temperatures of the various sites) results in higher SOC (16%) at lower and lower (-15.6%) at higher temperature (Figure 5), i.e. the sensitivity is practically constant over the temperature range of 21-27 °C. Above a temperature of 27 °C, there will be no further effect, as the temperature response function in the model levels off at 27 °C. A decrease (by 20%) in the initial relative mineralization rate, R, leads to a higher SOC (29%) and vice versa

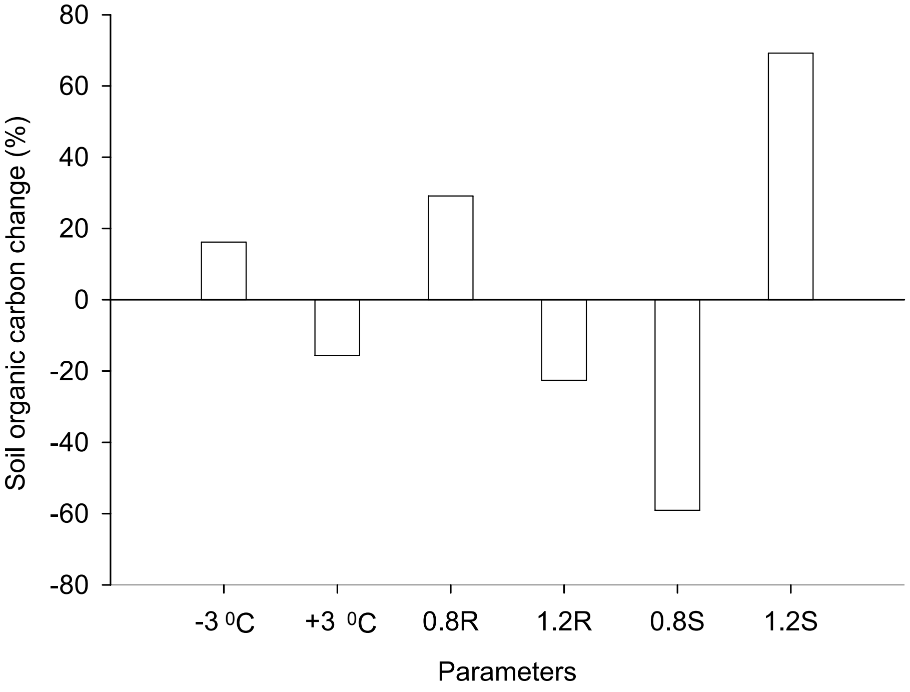

Figure 5. Cumulative changes (%) in soil organic carbon calculated for a period of 100 years with variations in model parameters (*R* and *S*) and in average ambient temperature.

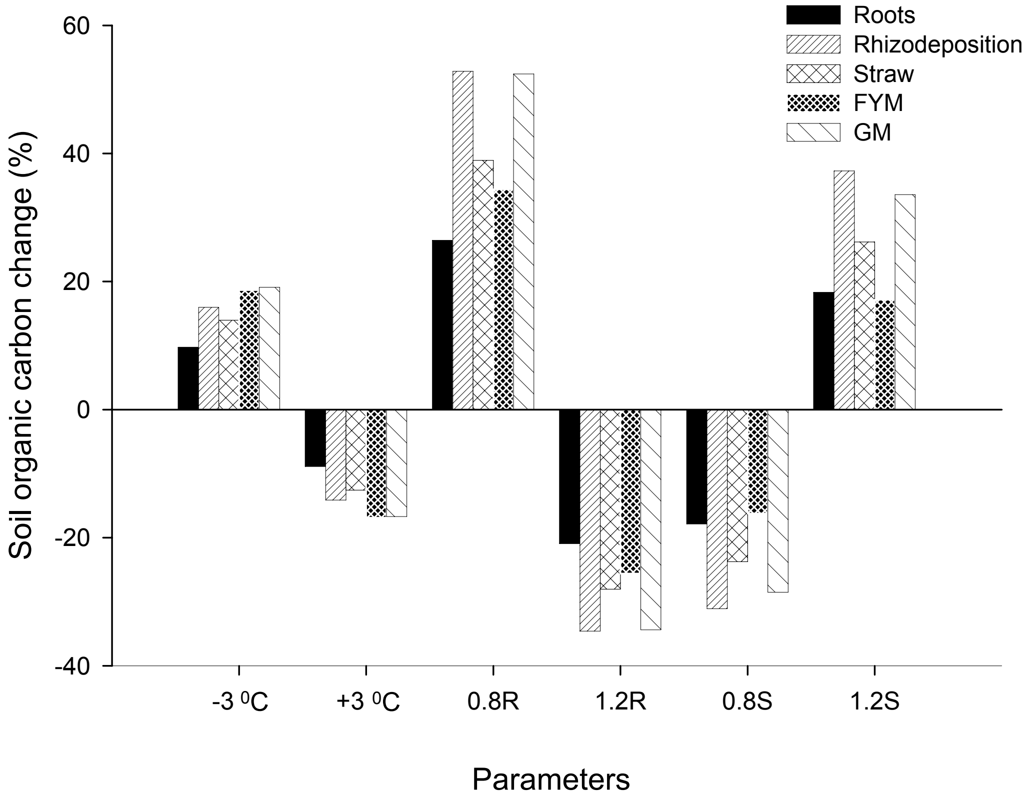

Figure 6. Changes (%) in fresh organic carbon of different organic amendments (over a period of 1 year) resulting from variations in model parameters (*R* and *S*) and in ambient temperature.

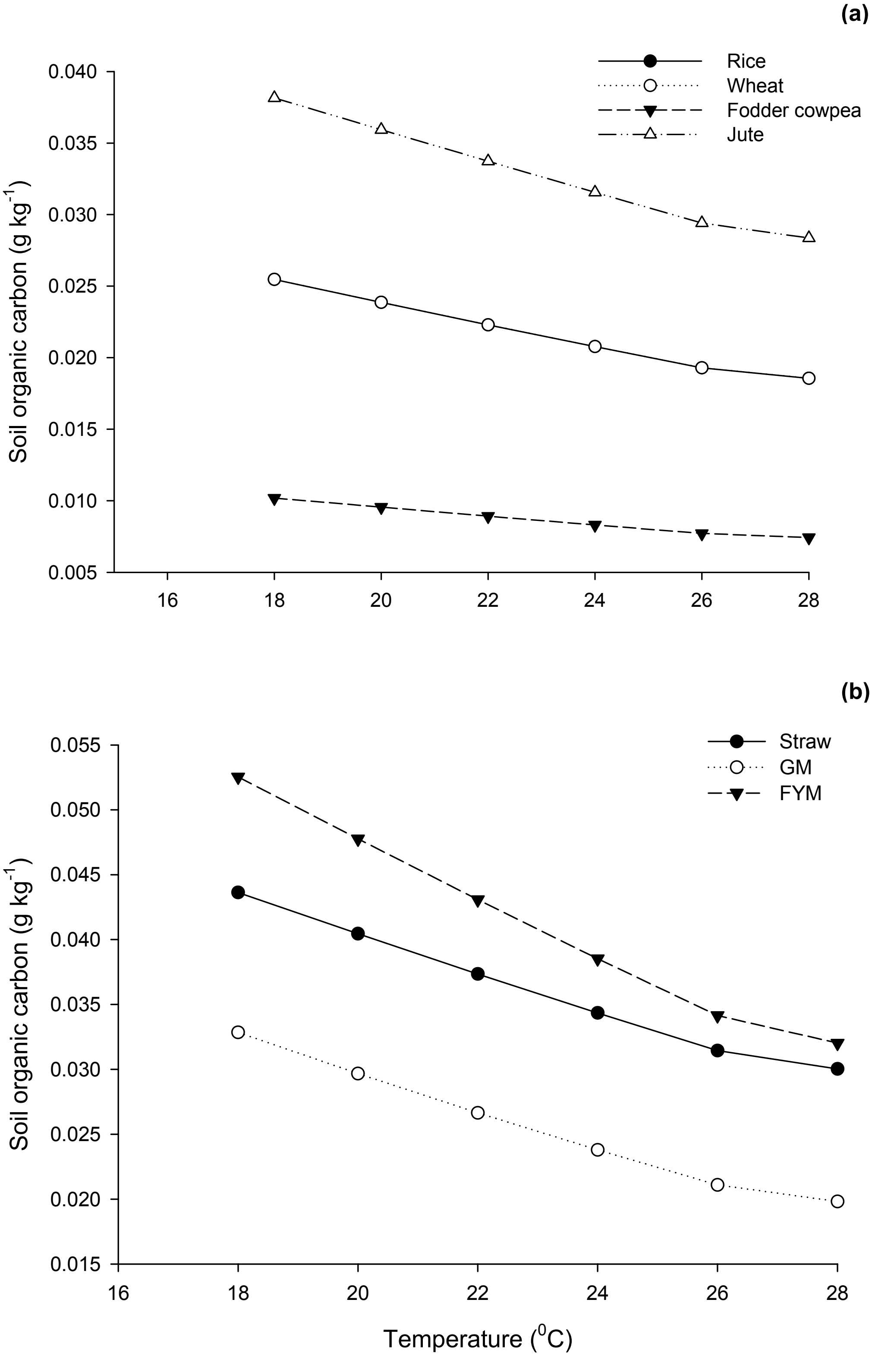

Figure 7. Potential increase in SOC after one year (a) resulting from an increase in yield (assuming no change in HI) of different crops by 1 Mg ha^{-1}; (b) an increase in addition of different organic amendments by 1 Mg ha^{-1}.

(-22.6%). Model results are more sensitive to changes in the value of S, the 'rate of ageing' of the substrates (Figure 5). A 20% increase in the S value results in a 69% higher SOC content, whereas a similar decrease results in 59% lower SOC content. An increase in S results in higher SOC content, due to faster ageing. For temperature and the model parameter R, the response of SOC content is linear over the range tested, whereas for S, the effect is non-linear, as this characteristic is in the power function of Eqn.3.

The sensitivity of different organic substrates to temperature varies for the different components and varies with time. As 70-90 percent of the added organic substrates disappear within 1 year, the sensitivity to variations in their addition is considered only for the first year (Figure 6). A decrease of 3 °C increases the residual carbon of the various substrates after one year by 14-19 percent and that of roots by 10 percent, while an increase in temperature by 3 °C reduces the residual carbon by 13-17 percent and that of roots by 9 percent. Modifying R- and S-values has differential influence on GM, rhizodeposition, straw, FYM and roots.

Increasing organic carbon input through higher crop yields and/or application of organic amendments has varying results, depending on crop and substrate (Figure 7). Since 70-90% of the carbon from freshly added organic substrates vanishes within a year of their application, in practice, about 25-75 kg of C (i.e. 3-8% of the corresponding yield) is effectively added to the soil per Mg grain yield of cereals, only from the contribution of roots and rhizodepositition. Therefore, an increase of 1 Mg ha^{-1} in crop yield (assuming a constant HI) can potentially increase SOC content by 0.01-0.04 g C kg^{-1} (for a bulk density of 1500 kg m^{-3}), depending on temperature, one year after its production. This potential increase is highest for jute, followed by rice and wheat (Figure 7a). For pulses, the effects of yield increases on SOC are smaller than those for cereals. Application of 1 Mg ha^{-1} organic amendments like FYM, straw and GM will result in addition of 40-120 kg C, which potentially could increase SOC by 0.02-0.05 g C kg^{-1} one year after its application (Figure 7b). The potential effect is strongest for FYM, followed by straw and GM.

Model application: Climate change and SOC - a scenario analysis

Projected changes in temperature, rainfall and atmospheric CO_2 in the future (Table 6) for Tropical Asia, including IGP, have been compiled by IPCC[5] (Watson et al., 1998; Lal et al., 2001). An increase in temperature will increase the decomposition rate of organic substrates (Jenkinson et al., 1991; Kirschbaum, 1995; 2000). However, final

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[5] Inter-Governmental Panel on Climate Change

Table 6. Projected effect of climate change on climatic factors.

Climatic factors	2010	2020	2050	2070	2080
Mean annual temperature increase, °C	0.5	1.36	2.69	-	3.84
CO_2, ppm	400	-	-	700	-
Rainfall change in Southwest monsoon region, %	-	2.9	6.8	-	11

(Sources: Watson et al., 1998; Lal et al., 2001; Aggarwal, 2003).

SOC content co-depends on carbon input through crop biomass and organic amendments, compensating the losses through decomposition. Simulation studies (Aggarwal and Mall, 2002; Aggarwal, 2003), assessing the effects of climate change on crop performance show variable impacts, depending on the assumed relative magnitude of changes in CO_2, temperature, and rainfall. An increase in temperature reduces crop growth duration and yield, while an increase in CO_2 through its 'fertilization' effect, leads to higher yields. Aggarwal (2003) considered two scenarios for 2070: 20-30 percent increase in yield (optimistic) and 20-30 decrease (pessimistic) under current (150 kg ha^{-1}) mineral nitrogen fertilizer rates. Based on these scenarios, and assuming a 25 percent increase or decrease by 2070, we extrapolated these figures to 2080 and have executed the model for three future situations: 1) current: with the current yields; 2) optimistic: 30% higher yields; 3) pessimistic: 30% lower yields. Simulations were carried out for different sites from the start of the experiments (Table 1), assuming an annual temperature increase of 0.0427 °C since 1990 to yield an increase of 3.84 °C by 2080. After the year 2000, average yield values for the base period of 1995-2000 were modified by an annual rate of ± 0.37%, until the year 2080 under the current crop management conditions.

Results of these scenario analyses (Figure 8) show that under the current scenario, in 2080 SOC content in Ludhiana-1 is 0.7 g kg^{-1} lower than the present level (4 g kg^{-1}). For Ludhiana-2, SOC initially (first 20 years) increases, followed by a continuous decrease. For Ludhiana-3, SOC content continuously decreases with time. Under the optimistic scenario, SOC is maintained almost at the current level in Ludhiana-1, and increases in Ludhiana-2, while in Ludhiana-3, it is 0.6 g kg^{-1} lower in 2080. Under the pessimistic scenario, in Ludhiana-2, SOC slightly increases up to 2020 and subsequently decreases. In Ludhiana-1 and Ludhiana-3, SOC continuously declines under this scenario. In Karnal, SOC increases under all three scenarios, except for the last thirty years under the pessimistic scenario, which may be unrealistic, as the model

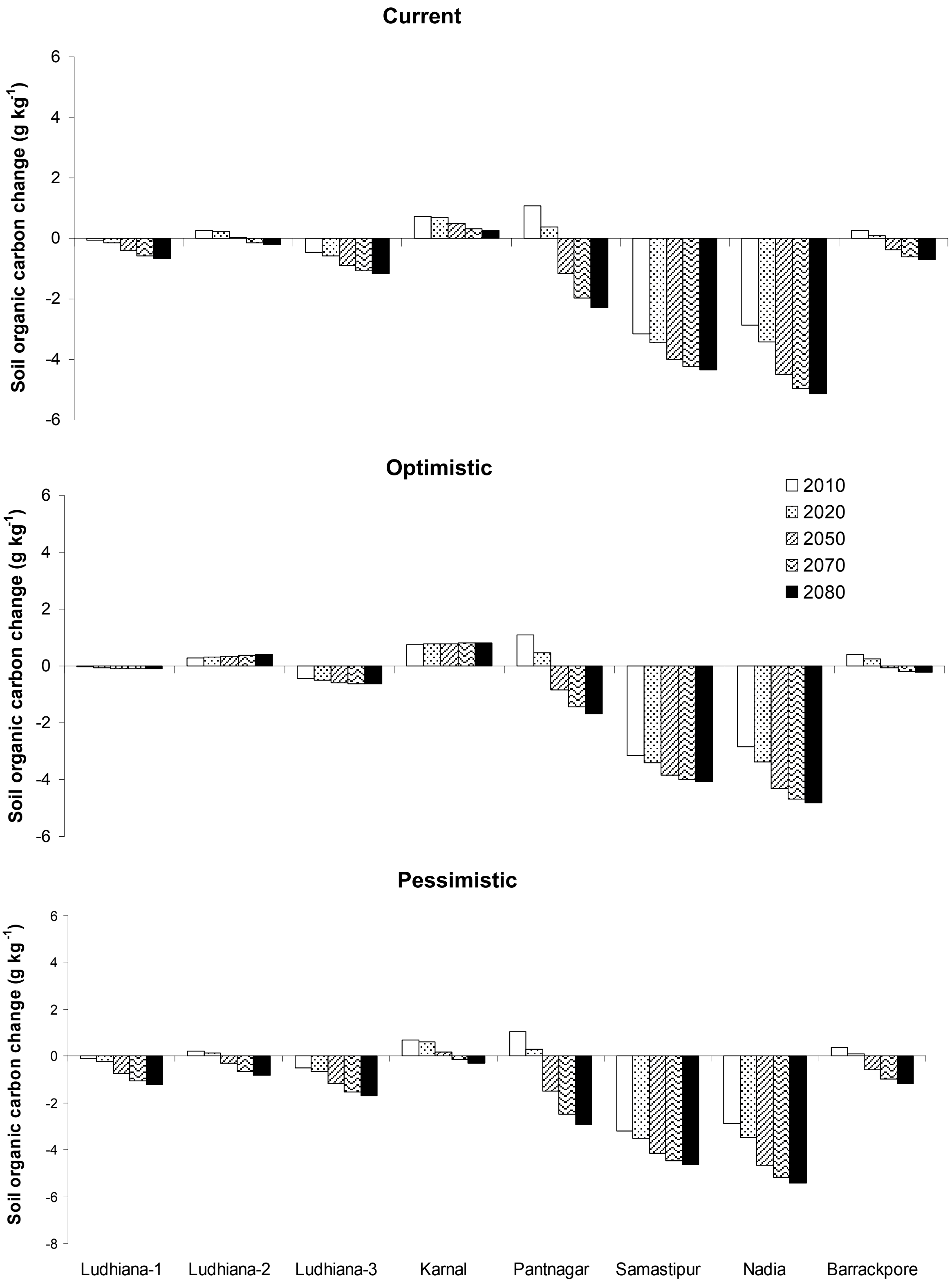

Figure 8. Projected changes in soil organic carbon (g kg^{-1}) for various study sites with projected increase in temperature of 3.84 °C (till the year 2080) under different scenarios: current- no change in crop yields; optimistic-30% increase in crop yields; pessimistic-30% decrease in crop yields.

does not account for the effect of the soil sodicity problems in this area. Pantnagar shows an increase in SOC content until 2010 under all three scenarios, followed by a decrease. In Samastipur and Nadia, SOC decreases under all three scenarios by 4.0- 5.4 g kg^{-1} by 2080. Barrackpore shows an increase in the first twenty years, followed by a decline in all three scenarios.

Conclusions

The simple first order equation for organic matter decomposition, used in this study has the advantage of a limited number of parameters, while satisfactorily describing long-term SOC dynamics. However, apart from temperature and pH, effects of site-specific factors such as soil texture, soil moisture regime, and soil management on SOC decomposition cannot be taken into account. Effects of flooding and transition between anaerobic and aerobic soil conditions, characteristic for rice-wheat cropping systems prevalent in the study area, on SOC decomposition are not considered in the model.

Soil organic carbon change is the result of the net balance of organic additions to the soil and SOC losses through decomposition. Therefore, in cropland, crop residue additions to the soil in the form of roots, rhizodeposition, straw and FYM and their rates of decomposition determine soil organic carbon content. In the approach illustrated in this paper, decomposition of indigenous soil organic carbon and added organic carbon are calculated independently of each other (although, in reality, part of the added organic material becomes part of SOC after some time, and then further decomposes), so that the uncertainty associated with estimation of many different SOC pools in many of the existing SOC models is avoided. The results of the study indicate that sites with initially low ($\leq$ 5 g kg^{-1}) organic C contents (Ludhiana-1, Ludhiana-2, Ludhiana-3, and Samastipur) show an increase in SOC under cultivation, since the organic carbon demand to maintain the initial level is low, and a moderate yield level with the associated carbon input increases the organic carbon level, even without additional external inputs. With addition of external organic amendments, carbon content increases substantially at these sites. On the other hand, at sites with relatively high SOC contents (> 5 g kg^{-1}, Pantnagar, Nadia, and Barrackpore) at the start of cultivation, SOC declines when only mineral fertilizers are applied. To maintain these organic carbon levels, seasonal additions of organic amendments is necessary in these situations, as the organic carbon losses through decomposition cannot be compensated only from crop inputs of roots and rhizodeposition.

Discrepancies between observed and model-calculated results for specific sites could be explained through the effect of high pH (Ludhiana-3), sodicity (Karnal), high $CaCO_3$ content (Samastipur) and soil erosion (Pantnagar). Therefore, model projections for these sites under different scenarios are also quite uncertain. For example, for Karnal, the possibility of an increase in SOC is unrealistic. Similarly, a continuous decline in SOC under all scenarios in Ludhiana-3 and Samastipur may neither be realistic.

To conclude, speculated yield decline in the IGP, which is 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. This would lead to a spiral of unsustainability, unless external organic amendments are added. Therefore, a sustainable production system requires integrated nutrient management with application of organic and inorganic fertilizers to increase biomass production and crop yield and thus carbon input into the soil.

References

Aggarwal, P.K., 2003. Impact of climate change on Indian agriculture. Journal of Plant Biology 30, 189-198.

Aggarwal, P.K. and Mall, R.K., 2002. Climate change and rice yields in diverse agro-environments of India. II. Effect of uncertainties in scenarios and crop models on impact assessment. Climatic Change 52, 331-343.

Bhandari, A.L., Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D. and Gupta, R.K., 2002. Yield and soil nutrient changes in a long-term rice-wheat rotation in India. Soil Science Society of America Journal 66, 162-170.

Bhattacharyya, T., Pal, D.K., Chandran, P., Mandal, C., Ray, S.K., Gupta, R.K. and Gajbhiye, K.S., 2004. Managing soil carbon stocks in the Indo-Gangetic Plains, India. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, 44 pp.

Bronson, K.F., Cassman, K.G., Wassman, R., Olk, D.C., van Noordwijk, M. and Garrity, D.P., 1998. Soil carbon dynamics in different cropping systems in principal ecoregions of Asia. In: Lal, R., Follet, R. F. and Stewart, B. A. (Eds.) Management of carbon sequestration in soil. CRC Press, Boca Raton, Florida, pp. 35-57.

Buyanovsky, G.A. and Wagner, G.H., 1998. Changing role of cultivated land in the global carbon cycle. Biology and Fertility of Soils 27, 242-245.

Cassman, K.G. and Pingali, P.L., 1995. Extrapolating trends from long-term experiments to farmer's fields: the case of irrigated rice systems in Asia. In: Barnett, V., Payne, R. and Steiner, R., (Eds.) Agricultural Sustainability in Economic, Environmental and Statistical terms. Wiley, London, pp. 64-84.

Chander, K., Goyal, S. and Kapoor, K.K., 1994. Effect of sodic water irrigation and farmyard manure application on soil microbial biomass and microbial activity. Applied Soil Ecology 1, 139-144.

Dawe, D., Dobermann, A., Moya, P., Abdulrachman, S., Singh, B., Lal, P., Li, S.Y., Lin, B., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., Tan, P.S. and Zhen, Q.X., 2000. How widespread are yield declines in long-term rice experiments in Asia? Field Crops Research 66, 175-193.

De Ridder, N. and Van Keulen, H., 1990. Some aspects of the role of organic matter in sustainable intensified arable farming systems in the West-African semi-arid tropics (SAT). Fertilizer Research 26, 299-310.

Dersch, G. and Bohm, K., 2001. Effects of agronomic practices on the soil carbon storage potential in arable farming in Austria. Nutrient Cycling in Agroecosystems 60, 49-55.

Duxbury, J.M., Abrol, I.P., Gupta, R.K. and Bronson, K.F., 2000. Analysis of long-term soil fertility experiments with rice-wheat rotations in South Asia. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K., (Eds.) Long-term soil fertility experiments with rice-wheat rotations in South Asia, Rice-Wheat Consortium Paper Series 6, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, pp. 7-22.

Gajri, P.R. and Prihar, S.S., 1985. Rooting, water-use and yield relations in wheat on loamy sand and sandy loam soils. Field Crops Research 12, 115-132.

Gaur, A.C. and Singh, R., 1982. Integrated nutrient supply systems. Fertilizer News 27, 87-98.

Gupta, R.K., 2003. The rice-wheat consortium for the Indo-Gangetic Plains: vision and management structure. Addressing resource conservation issues in rice-wheat systems for South Asia: A resource book. Rice Wheat Consortium-CIMMYT, New Delhi, pp. 1-7.

Haverman, P.P., 1986. Characterisation of the growth of a cowpea crop (Vigna unguiculata (L.) Walp.) Cv. 59 - 25 in the Sahelian Zone. Wageningen Agricultural University, Wageningen, The Netherlands, 86 pp.

Havlin, J.L., Kissel, D.E., Maddux, L.D., Claassen, M.M. and Long, J.H., 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Science Society of America Journal 54, 448-452.

Holeplass, H., Singh, B.R. and Lal, R., 2004. Carbon sequestration in soil aggregates under different crop rotations and nitrogen fertilization in an inceptisol in southeastern Norway. Nutrient Cycling in Agroecosystems 70, 167-177.

Janssen, B.H., 1984. A simple method for calculating decomposition and accumulation of young soil organic matter. Plant and Soil 76, 297-304.

Jenkinson, D.S. and Rayner, J.H., 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Science 123, 298-305.

Jenkinson, D.S. and Ayanaba, A., 1977. Decomposition of C-14-labeled plant material under tropical conditions. Soil Science Society of America Journal 41, 912-915.

Jenkinson, D.S., Adams, D.E. and Wild, A., 1991. Model estimates of CO_2 emissions from soil in response to global warming. Nature 351, 304-306.

Jenkinson, D.S., Harkness, D.D., Vance, E.D., Adams, D.E. and Harrison, A.F., 1992. Calculating net primary production and annual input of organic matter to soil from the amount and radiocarbon content of soil organic matter. Soil Biology and Biochemistry 24, 295-308.

Jenny, H., 1981. The soil resource. Ecological Studies, Vol. 37, Springer-Verlag, New York, USA, 377 pp.

Johansen, C., Waseque, M., Ahmed, M.M. and Begum, S., 1985. Plant growth curves and fiber quality changes of jute (Corchorus spp) grown in Bangladesh. Field Crops Research 12, 387-395.

Katyal, J.C., Rao, N.H. and Reddy, M.N., 2001. Critical aspects of organic matter management in the tropics: the example of India. Nutrient Cycling in Agroecosystems 61, 77-88.

Katyal, V.V., 2001. Conservation of organic carbon in relation to crop productivity, yield stability and soil fertility under rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system. Indian Journal of Agronomy 46, 1-4.

Keith, H., Oades, J.M. and Martin, J.K., 1986. Input of carbon to soil from wheat plants. Soil Biology and Biochemistry 18, 445-449.

Khan, U., Mishra, B., Pachauri, P. and Kumar, Y., 2006. Effect of integrated management on yield and nitrogen nutrition of irrigated rice. Indian Journal of Agricultural Sciences 76, 176-180.

Kirschbaum, M.U.F., 1995. The temperature dependence of soil organic matter decomposition and the effect of global warming on soil organic C storage. Soil Biology and Biochemistry 27, 753-760.

Kirschbaum, M.U.F., 2000. Will changes in soil organic carbon act as a positive or negative feedback on global warming? Biogeochemistry 48, 21-51.

Kogel-Knabner, I., 2002. The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter. Soil Biology and Biochemistry 34, 139-162.

Kolenbrander, G.J., 1969. De bepaling van de waarde van verschillende soorten organische stof ten aanzien van hun effect op het humusgehalte bij bouwland. Instituut voor Bodemvruchtbaarheid, Haren, The Netherlands, 17 pp.

Kundu, A.L. and Samui, R.C., 2000. Long-term soil fertility experiment in rice-wheat cropping system in West Bengal. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K. (Eds.) Long-term soil fertility experiments with rice-wheat rotations in South Asia. Rice-Wheat Consortium Paper Series 6, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 63-67.

Kundu, B.C., Basak, K.C. and Sarcar, P.B., 1959. Jute in India. The Indian Central Jute Committee, Calcutta, India, pp. 71-87.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K. and Hobbs, P.R., 2003. How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crops Research 81, 159-180.

Lal, M., Harasawa, H. and Murdiyarso, D., 2001. Asia. In: McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J. and White, K. S. (Eds.) Climate change 2001: Impacts, adaptation, and vulnerability. IPCC Report, Cambridge University Press, UK, pp. 1005

Lal, R., 2002. Soil carbon dynamics in cropland and rangeland. Environmental Pollution 116, 353-362.

Laura, R.D., 1973. Effects of sodium carbonate on carbon and nitrogen mineralisation of organic matter added to soil. Geoderma 9, 15-26.

Laura, R.D., 1976. Effects of alkali salts on carbon and nitrogen mineralization of organic matter in soil. Plant and Soil 44, 587-596.

Manna, M.C., Swarup, A., Wanjari, R.H., Singh, Y.V., Ghosh, P.K., Singh, K.N., Tripathi, A.K. and Saha, M.N., 2006. Soil organic matter in a West Bengal Inceptisol after 30 years of multiple cropping and fertilization. Soil Science Society of America Journal 70, 121-129.

Nambiar, K.K.M., 1995. Major cropping systems in India. In:Barnett, V, Payne, R., Steiner R. (Eds) Agricultural sustainability: Economic, Environmental, and Statistical considerations. Wiley, London, pp. 133-170.

Narang, R.S. and Virmani, S.M., 2001. Rice-wheat cropping systems of the Indo-Gangetic Plains of India. Rice-Wheat Consortium Paper Series 11, Rice-Wheat

Consortium for the Indo-Gangetic Plains, New Delhi and International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradesh, India, 36 pp.

Noij, I.G.A.M., Janssen, B.H., Wesselink, L.G. and van Grinsven, J.J.M., 1993. Modelling nutrient and moisture cycling in tropical forests. Tropenbos Series 4, Wageningen, The Netherlands, 195 pp.

Palit, P., 1985. Translocation and distribution of ^{14}C-labelled assimilate associated with growth of jute (Corchorus olitorius L.). Australian Journal of Plant Physiology 12, 527-534.

Palit, P. and Bhattacharya, A.C., 1982. Source-sink control of jute productivity. Indian Journal of Plant Physiology 25, 187-200.

Pieri, C., 1989. Fertilité des terres de savanne. Bilan de trente ans de recherche et de développement agricole au Sud du Sahara. Ministère de la Coopération et CIRAD, Paris, France, 444 pp.

Prasad, B. and Sinha, S.K., 2000. Long-term effects of fertilizers and organic manures on crop yields, nutrient balance, and soil properties in rice-wheat cropping system in Bihar. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K. (Eds.) Long-term soil fertility experiments with rice-wheat rotations in South Asia. Rice-Wheat Consortium Paper Series 6, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 105-119.

Ram, N., 1995. Long-term effects of fertilizers on crop production and soil properties in a Mollisol. Technical Research Bulletin 124, G.B. Pant University of Agriculture and Technology, Pantnagar, India, 36 pp.

Ram, N., 1998. Effect of continuous fertilizer use on soil fertility and productivity of a Mollisol. In: Swarup, A., Damodar, R. D. and Prasad, R. N. (Eds.) Long-term soil fertility management through integrated plant nutrient supply. All India Coordinated Research Project (AICRP) on long-term fertilizer experiments, Indian Institute of Soil Science, Bhopal, India, pp. 229-237.

Ram, N., 2000. Long-term effects of fertilizers on rice-wheat-cowpea productivity and soil properties in Mollisols. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K. (Eds.) Long-term soil fertility experiments with rice-wheat rotations in South Asia. Rice-Wheat Consortium Paper Series 6, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 50-55.

Rasmussen, P.E., Allmaras, R.R., Rohde, C.R. and Roager, N.C. Jr., 1980. Crop residue influences on soil carbon and nitrogen in a wheat-fallow system. Soil Science Society of America Journal 44, 596-600.

Saha, M.N., Chaudhury, J., Saha, A.R. and Ray, P.K., 1998. Effect of intensive cropping and fertilizer use on soil properties and crop yields in a long-term experiment. In: Swarup, A., Reddy, D. D. and Prasad, R. N. (Eds.) Long-term soil fertility management through integrated plant nutrient supply. Indian Institute of Soil Science, Bhopal, India, pp. 215-220.

Saha, M.N., Saha, A.R., Mandal, B.C. and Ray, P.K., 2000. Effects of long-term jute-rice-wheat cropping system on crop yields and soil fertility In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K. (Eds.) Long-term soil fertility experiments with rice-wheat rotations in South Asia. Rice-Wheat Consortium Paper Series 6, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 94-104.

Samui, R.C., Kundu, A.L., Mazumdar, D. and Mani, P.K., 1998. Integrated nutrient management in rice-wheat system in West-Bengal. In: Swarup, A., Reddy, D. D. and Prasad, R. N. (Eds.) Long-term soil fertility management through integrated plant nutrient supply. Indian Institute of Soil Science, Bhopal, India, pp. 256-259.

Sanchez, P.A., 1976. Properties and management of soils in the tropics. John Wiley & Sons, New York, USA, 618 pp.

Sauerbeck, D.R. and Gonzalez, M.A., 1977. Field decomposition of carbon-14-labelled plant residues in various soils of the Federal Republic of Germany and Costa Rica. Soil organic matter studies. Proceedings of a Symposium organized by IAEA, FAO and Agrochimica, Braunschweig, pp. 159-170.

Sauerbeck, D.R. and Johnen, B.G., 1977. Root formation and decomposition during plant growth. Soil organic matter studies. Proceedings of a Symposium organized by IAEA, FAO and Agrochimica, Braunschweig, pp. 141-148.

Shamoot, S., Mcdonald, L. and Bartholomew, W.V., 1968. Rhizodeposition of organic debris in soil. Soil Science Society of America Proceedings 32, 817-820.

Sidhu, B.S. and Beri, V., 1989. Effect of crop residue management on the yields of different crops and on soil properties. Biological Wastes 27, 15-27.

Singh, B.R., Børresen, T., Uhlen, G. and Ekeberg, E., 1998. Long-term effects of crop rotation, cultivation practices and fertilizers on carbon sequestration in soils in Norway. In: Lal, R., Kimble, J. M., Follet, R. F. and Stewart, B. A. (Eds.) Management of carbon sequestration in soil. CRC Press, Boca Raton, FL, pp. 195-208.

Six, J., Bossuyt, H., Degryze, S. and Denef, K., 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Research 79, 7-31.

Terao, T., Watanabe, I., Matsunaga, R., Hakoyama, S. and Singh, B.B., 1997. Agro-physiological constraints in intercropped cowpea: an analysis. In: Singh, B. B., Mohan Raj, D. R., Dashiell, K. E. and Jackai, L. E. N. (Eds.) Advances in cowpea research. International Institute of Tropical Agriculture, Ibadan, Nigeria and Japan International Research Centre for Agricultural Sciences, Tsukuba, Ibaraki, Japan, pp. 129-140.

Thakur, R.C., Bindra, A.D., Sood, R.D. and Bhargava, M., 1995. Effect of fertilizer application and green manuring on physicochemical properties of soil and grain yield in rice (*Oryza sativa*) wheat (*Triticum aestivum*) crop sequence. Indian Journal of Agronomy 40, 4-13.

Tisdall, J.M. and Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. European Journal of Soil Science 33, 141-163.

Van Wambeke, A., 1992. Soils of the tropics-properties and appraisal. Mc Graw-Hill, New York, USA, 343 pp.

Watson, R.T., Zinyowera, M.C. and Ross, R.H. 1998. The regional impacts of climate change: an assessment of vulnerability. IPCC Report II, Cambridge University Press, Cambridge, UK, 517 pp.

Wisserhof, K., 1995. Developing a simulation model for the growth of cowpea (Vigna unguiculata (L.), with special attention to the phosphorus balance and nitrogen fixation. Wageningen Agricultural University, Wageningen, The Netherlands, 84 pp.

Wong, V.N.L., Greene, R.S.B., Murphy, B.W., Dalal, R. and Mann, S., 2004. Carbon dynamics in salt-affected soils In: Roach, I.C. (Ed.) Proceedings of the CRC LEME Regional Regolith Symposia, University of Adelaide, Australia, pp. 407-410.

Yaduvanshi, N.P.S., 2001. Effect of five years of rice-wheat cropping and NPK fertilizer use with and without organic and green manures on soil properties and crop yields in a reclaimed sodic soil. Journal of Indian Society of Soil Science 49, 714-719.

Yadvinder, S., Singh, B., Meelu, O.P. and Khind, C.S., 2000. Long-term effects of organic manuring and crop residues on the productivity and sustainability of rice-wheat cropping system in Northwest India. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K. (Eds.) Long-term soil fertility experiments in rice-wheat cropping systems. Rice-Wheat Consortium Paper Series 6, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 149-162.

Yadvinder, S., Bijay, S., Ladha, J.K., Khind, C.S., Khera, T.S. and Bueno, C.S., 2004b. Effects of residue decomposition on productivity and soil fertility in rice-wheat rotation. Soil Science Society of America Journal 68, 854-864.

Yadvinder, S., Bijay, S., Ladha, J.K., Khind, C.S., Gupta, R.K., Meelu, O.P. and Pasuquin, E., 2004a. Long-term effects of organic inputs on yield and soil fertility in the rice-wheat rotation. Soil Science Society of America Journal 68, 845-853.

Yang, H.S., 1996. Modelling organic matter mineralization and exploring options for organic matter management in arable farming in Northern China, Ph.D. Thesis, Wageningen Agricultural University, Wageningen, The Netherlands, 159 pp.

Yang, H.S. and Janssen, B.H., 2000. A mono-component model of carbon mineralization with a dynamic rate constant. European Journal of Soil Science 51, 517-529.

Yoshida, S., 1981. Fundamentals of rice crop science. International Rice Research Institute, Los Baños, Philippines, 269 pp.

CHAPTER 4

LINTUL3, a simulation model for nitrogen-limited situations: application to rice

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Abstract

LINTUL3 is a general crop model that calculates biomass production based on intercepted photosynthetically active radiation (PAR) and light use efficiency (LUE). It is an extended version of LINTUL2 (simulates potential and water-limited crop growth), including nitrogen limitation. However, in the present study, water shortage is not considered, as the crop considered is paddy rice and therefore, the model results correspond to nitrogen-limited yield. Nitrogen stress in the model is defined through the nitrogen nutrition index (NNI), the ratio of actual nitrogen concentration to critical nitrogen concentration in the plant. Nitrogen stress affects crop growth through a proportional reduction in leaf area growth, accelerated senescence, reduced biomass partitioning to leaves, and translocation of stem reserves to the storage organs. This paper describes the model with application to rice, its calibration and validation using independent data sets of nitrogen treatments (with fertilizer rates of 0 to 400 kg N ha^{-1}) under varying environmental conditions in Asia: International Rice Research Institute, Philippines and Central Rice Research Institute, India, during 1990–1993. Results of calibration and validation are compared graphically, through root mean square deviation (RMSD), and average absolute deviation (AAD). Results of model calibration and validation show that model results are comparable to the observations. Average absolute deviation values for calibration and validation of total aboveground biomass show less than 25 percent mean deviation from the observations, whereas stems and storage organs show mean variations up to 50 percent.

Keywords: Calibration, crop growth, CRRI, IRRI, nutrition index, validation

Introduction

Photosynthesis, in which atmospheric carbon is fixed into carbohydrates, is the basis of biomass production. Nitrogen (N) availability affects photosynthesis through its impact on leaf area and photosynthetic capacity (Novoa and Loomis, 1981; Van Keulen et al., 1988), as nitrogen is the major structural component of chlorophyll. Under ample nitrogen supply (assuming no limitations for water and other nutrients), N accumulation in the crop is mostly determined by intrinsic crop characteristics (Gastal and Lemaire, 2002). Under nitrogen-deficient conditions, N content in the plant is lower and carbon accumulation is negatively affected. The reduction in biomass production in response to N deficiency is associated with either a reduction in total radiation intercepted by the canopy, or by a decrease in the efficiency with which the intercepted radiation is used to produce dry matter, or a combination of both (Muchow, 1990). Actual crop nitrogen content is determined by nitrogen availability in the soil, which depends on the dynamics of various components of the nitrogen cycle in the root zone that are determined by soil, crop and management factors. Well-validated simulation models, quantitatively describing the processes of the nitrogen balance in the soil, nitrogen uptake by the crop and crop growth, are useful tools to understand and explore changes in crop growth in response to changes in nitrogen management (Van Ittersum et al., 2003). However, a major constraint for application of complex process-based simulation models is their large data requirements, many of which are difficult to measure in a field situation. Simple crop models, with limited data requirements, can alleviate this constraint (Spitters, 1990). LINTUL (Light INTerception and UtiLization simulator) is such a simple crop model that simulates dry matter production as a function of light interception using constant light use efficiency (LUE; Van Oijen, 1992). LINTUL, developed for potential crop growth as LINTUL1 (Spitters, 1990), has later been extended to take into account water-limited conditions (LINTUL2) (Spitters and Schapendonk, 1990). LINTUL has been successfully applied to different crops such as potato (Spitters and Schapendonk, 1990), grassland (LINGRA) (Schapendonk et al., 1998), maize (Farré et al., 2000) and oilseed rape (Habekotté, 1997) in potential and water-limited situations. LINTUL3, described in this paper, is an extension of LINTUL2 and includes a description of the effects of nitrogen limitation on biomass production, with application to rice.

Model description

The original version of LINTUL (Spitters, 1987) is a potential crop growth model where the yield of storage organs is calculated via application of a harvest index (HI) to total aboveground biomass, simulated directly from intercepted light and LUE. In LINTUL1, the total biomass formed is partitioned into roots, stems, leaves and storage organs (Spitters, 1990; Van Oijen, 1992). Water-limited crop growth (LINTUL2) (Spitters and Schapendonk, 1990; Farré et al., 2000) includes soil water processes such as evapotranspiration, drainage and runoff. The LINTUL3 model describes nitrogen demand and uptake by the crop in detail and soil nitrogen supply in a more simplified form. The effect of crop nitrogen deficiency is expressed via a growth reduction factor, the nitrogen nutrition index (NNI), which affects leaf growth. The following section describes the processes in the LINTUL3 model briefly.

Crop phenology

Temperature

Crop development, i.e. the order and rate of appearance of vegetative and reproductive organs, is defined in terms of phenological developmental stage (DVS) as a function of *heat sum*, i.e. cumulative daily effective temperature. Daily effective temperature is the average temperature above a base temperature, which is crop specific (for rice 8 °C). Development stage ranges from 0 (sowing) via 1 (flowering) to 2 (physiological maturity). Based on observed dates of sowing, transplanting, flowering (anthesis) and maturity in the field, heat sums corresponding to these development stages ($H_{sum,\ ant}$ for anthesis, $H_{sum,\ mat}$ for maturity) were calculated from the weather data for each specific year/season. Intermediate values of development stages are calculated as the ratio of current heat sum and the heat sums for anthesis and maturity, respectively.

Daylength

Some rice varieties are photoperiod-sensitive, i.e. flowering depends on the length of the light period in addition to the temperature during the vegetative stage. The optimum photoperiod range is 8–10 hours (Vergara and Chang, 1985). As even low light intensities are effective for daylength response (Wormer, 1954), photoperiodic daylength exceeds astronomical daylength. Photoperiodic daylength (L_d) is calculated in the model as a function of solar elevation (i.e. angle of sun above the horizon), determined by latitude and day of the year (Goudriaan and Van Laar, 1994):

$$\begin{aligned} L_d &= 12 + 24/\pi \operatorname{asin}[\mathrm{sinLD}/\mathrm{cosLD}] \\ \mathrm{sinLD} &= \sin\delta \sin\lambda \\ \mathrm{cosLD} &= \cos\delta \cos\lambda \end{aligned}$$

where sinLD is the seasonal offset of the sine of solar height; cosLD is the amplitude of the sine of solar height; δ is the solar declination in radians, and λ is the latitude in radians.

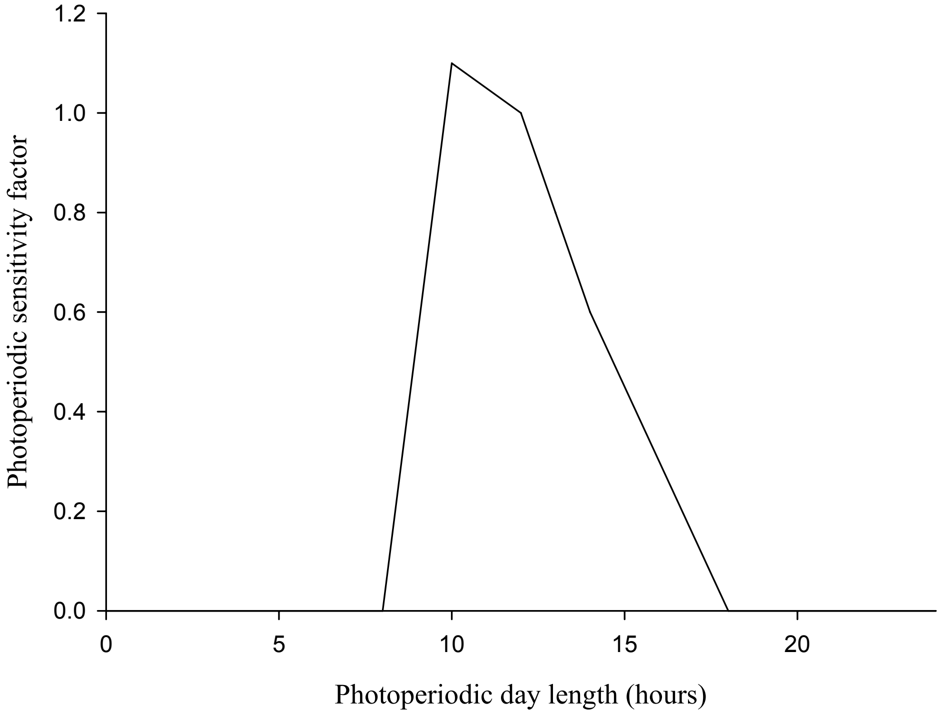

Figure 1. Photoperiodic sensitivity as a function of photoperiodic daylength, obtained by calibration.

Photoperiodic daylength-sensitivity, defined as a function of daylength (Figure 1) is included in the model through modification of the daily increment of temperature sum.

Light use efficiency and biomass production

Theoretical considerations and extensive experimentation (Monteith, 1977; Gallagher and Biscoe, 1978; Monteith, 1990) have shown that biomass formed per unit intercepted light, LUE (Light Use Efficiency, g dry matter MJ^{-1}) is constant. Hence, maximum daily growth rate can be defined as the product of intercepted PAR (photosynthetically active radiation) and LUE. Intercepted PAR depends on incident solar radiation, the fraction that is photosynthetically active (0.5) (Monteith and Unsworth, 1990; Spitters, 1990), and LAI (Leaf Area Index, m^2 leaf m^{-2} soil) according to Lambert-Beer’s law:

$$Q = 0.5\ Q_0\,[1 - \exp^{(-k\ LAI)}]$$

where Q is intercepted PAR ($MJ\ m^{-2}\ d^{-1}$), Q_0 is daily global radiation ($MJ\ m^{-2}\ d^{-1}$), and k the extinction coefficient for PAR.

For a single leaf, the relation between PAR interception and photosynthesis follows a saturation-type curve, indicating decreasing LUE with increasing light intensities. Similarly, instantaneous canopy photosynthesis tends to saturate at higher irradiance (Grace et al., 1995; Ruimy et al., 1995). However, as in field crops most of the leaves are exposed to non-saturating intensities for the greater part of the day, LUE on a daily basis is constant (Monteith, 1977; Spitters, 1990; Sinclair, 1991; Ruimy et al., 1995; Sinclair and Muchow, 1999; Rosati and DeJong, 2003).

Biomass partitioning

Biomass formed at any time during crop growth is partitioned among its organs (Figure 2), i.e. roots, stems, leaves and storage organs, with partitioning factors defined as a function of development stage (Figure 3) (Drenth et al., 1994), which thus provides the rates of growth of these organs:

$$\left(\frac{\mathrm{dW}}{\mathrm{dt}}\right)_{\mathrm{i}} = \mathrm{Pc}_{\mathrm{i}}\left(\frac{\mathrm{dW}}{\mathrm{dt}}\right)$$

where (dW/dt) is the rate of biomass growth (g m^{-2} d^{-1}); $(\mathrm{dW/dt})_{\mathrm{i}}$ and Pc_{i} are the rate of growth (g m^{-2} d^{-1}) of and biomass partitioning factor to organ *i*, respectively.

Leaf, stem and root weights of seedlings at the time of transplanting are input parameters for the model. The time course of weights of these organs follows from integration of their net rates of growth, i.e. growth rates minus death rates, the latter defined as a function of physiological age(ing), shading and stress.

Leaf area development

The time course of LAI is calculated in two stages: an initial exponential stage during the juvenile phase, where leaf area growth is a function of temperature, and a linear stage where it is dependent on increase in leaf biomass. In the juvenile phase, growth is sink-limited, determined by the number of cells capable of expansion and their rates of expansion, which is assumed to cease, somewhat arbitrarily, at DVS > 0.2 or LAI > 0.75. Following the juvenile stage, leaf area growth is assumed source-limited, and dependent on leaf weight growth rate and specific leaf area, the area per unit leaf weight. Specific leaf area is defined as a function of development stage (Figure 4). Leaf area growth rate (m^{2} m^{-2} d^{-1}) during the exponential (sink-limited) $(\mathrm{dGLAI/dt})_{\mathrm{exp}}$ and source-limited $(\mathrm{dGLAI/dt})_{\mathrm{sl}}$ growth stages is calculated as:

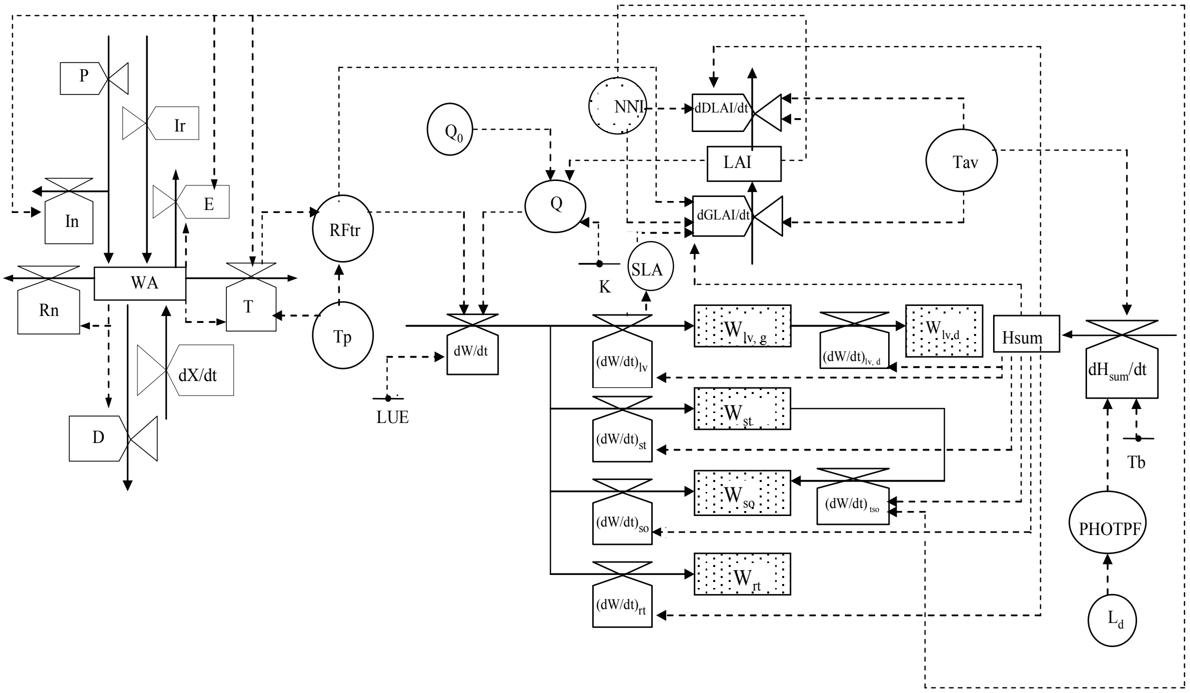

Figure 2. Relational diagram of the LINTUL3 model

Abbrevations used in the diagram: P- precipitation; Ir- irrigation; In- intercepted part of rain; E- evaporation; Rn- run off; T- transpiration; dX/dt- water exploration; D- drainage; WA- amount of water; RFtr- reduction factor for water stress; Tp- potential transpiration; Q_0- daily global radiation; Q- Intercepted PAR; K- light extinction coefficient; LUE- light use efficiency; dW/dt- rate of biomass production; $(dW/dt)_{lv}$- growth rate of leaves; $(dW/dt)_{st}$- growth rate of stems; $(dW/dt)_{so}$- growth rate of storage organs; $(dW/dt)_{tso}$- biomass translocated from stems to storage organs; $(dW/dt)_{rt}$- growth rate of roots; $W_{lv,g}$- weight of green leaves; $W_{lv,d}$- weight of dead leaves; W_{st}- weight of stems; W_{so}- weight of storage organs; W_{rt}- weight of roots; LAI- leaf area index; NNI- nitrogen nutrition index; dGLAI/dt- rate of increase in leaf area; dDLAI/dt- rate of decrease in leaf area; Tav- daily average temperature; Tb- base temperature for crop development; dH_{sum}/dt- rate of increase in temperature sum; Hsum- temperature sum; PHOTPF-Photoperiodic daylength sensitivity factor; L_d- day length; SLA: Specific leaf area.

Solid lines and dotted lines are indicating material and information flows, respectively, and shaded structures indicate that they are linked to Figure 5.

$$\left(\frac{\text{dGLAI}}{\text{dt}}\right)_{\text{exp}} = \text{LAI}_t\ \text{RL}\ T_e \qquad \text{DVS} < 0.2 \text{ and LAI} < 0.75$$

$$\left(\frac{\text{dGLAI}}{\text{dt}}\right)_{\text{sl}} = \left(\frac{\text{dW}}{\text{dt}}\right)_{\text{lv}} S_{\text{la}} \qquad \text{DVS} \geq 0.2 \text{ or LAI} \geq 0.75$$

where LAI_t is leaf area index at time t, RL the maximum relative growth rate of LAI ((°C d)$^{-1}$); T_e daily effective temperature (°C), $(dW/dt)_{lv}$ rate of dry matter growth of leaves (g m^{-2} d^{-1}), and S_{la} specific leaf area (m^2 g^{-1}).

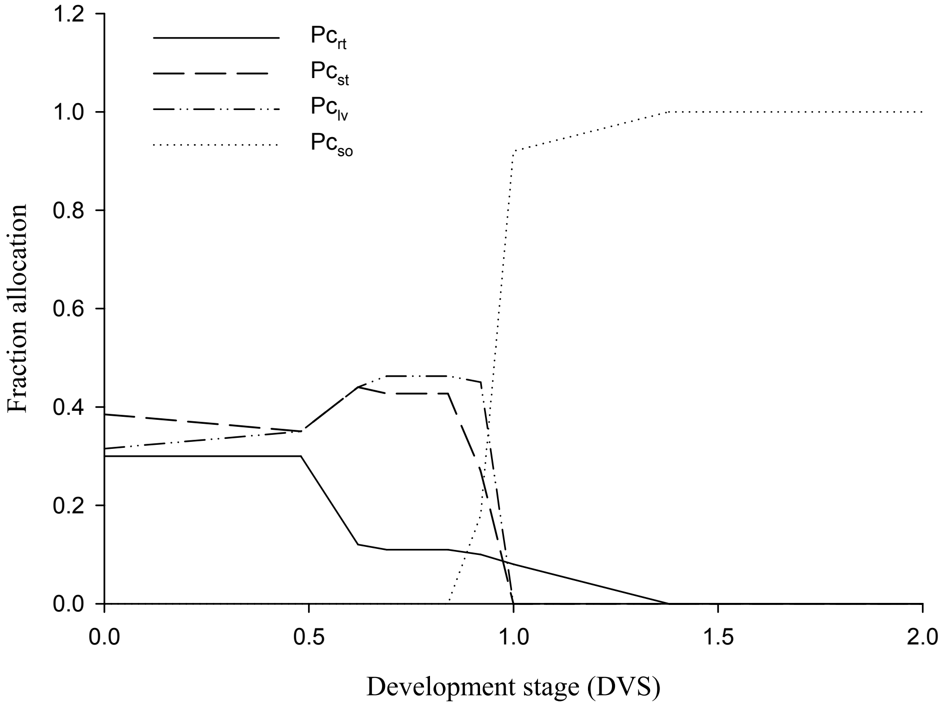

Figure 3. Partitioning coefficients of biomass increase to roots (Pc_{rt}), stem (Pc_{st}), leaves (Pc_{lv}) and storage organs (Pc_{so}) as a function of development stage.

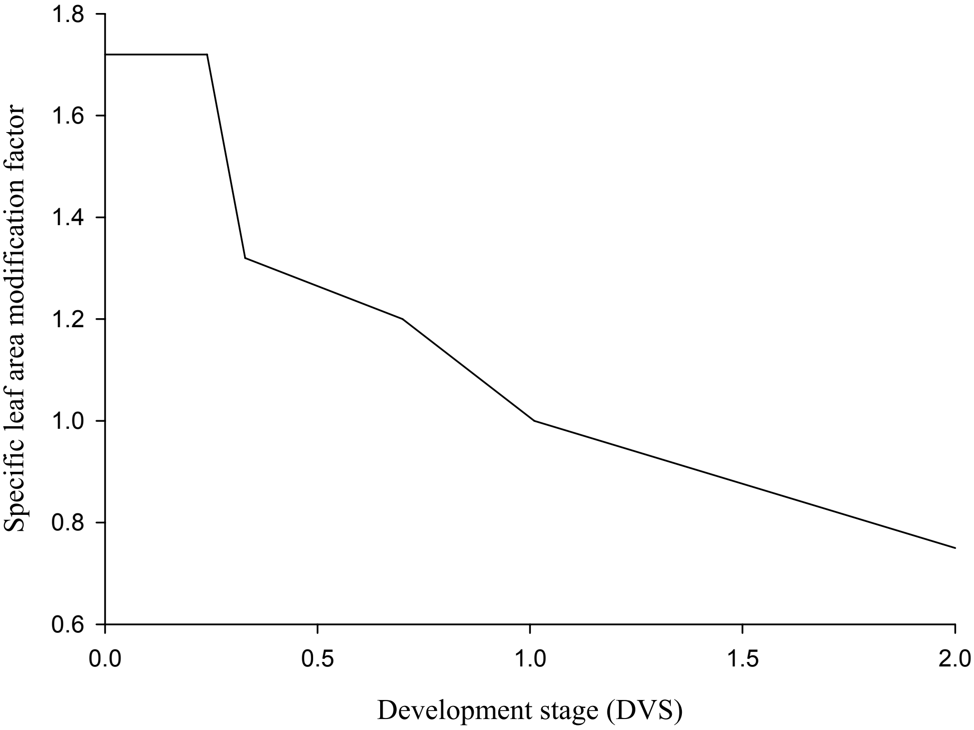

Figure 4. Specific leaf area modification function, depending on development stage.

Death of leaves due to senescence or to shading and/or stress leads to corresponding loss in leaf area, using average specific leaf area for the conversion. The net rate of change in leaf area is the difference between its growth rate and its death rate:

$$\frac{\mathrm{dLAI}}{\mathrm{dt}} = \left(\frac{\mathrm{dGLAI}}{\mathrm{dt}}\right) - \left(\frac{\mathrm{dDLAI}}{\mathrm{dt}}\right)$$

Root growth

The root system is characterized by its vertical extension in the soil profile. At emergence or at transplanting for transplanted rice, rooting depth is initialized. Roots elongate at a constant daily rate, until flowering, provided soil water content is above permanent wilting point (PWP) and growth ceases when soil is drier than PWP. However, in rice in a flooded situation, soil will always be at saturation.

Soil water balance

The water balance in the model does not deal with a flooded-rice system, but the soil is maintained at saturation such that the crop does not experience water stress. In the model, the soil water balance is considered for a single soil layer, whose thickness increases as roots elongate, i.e. as roots grow, soil depth increases. Water and nutrient uptake by the crop is limited to the rooted soil depth. Addition of water to the available store through root extension is calculated from the rate of extension and the water content, which is at saturation. The net rate of change in soil water content in the root zone (mm d^{-1}) is the balance of water added through rainfall (P, minus interception by the canopy (In)), irrigation (Ir) and root growth (dX/dt), and that lost through runoff (Rn), transpiration (T), evaporation (E), and drainage (D):

$$\frac{\mathrm{dW}}{\mathrm{dt}} = (\mathrm{P} + (\mathrm{dX/dt}) + \mathrm{Ir}) - (\mathrm{In} + \mathrm{Rn} + \mathrm{T} + \mathrm{E} + \mathrm{D})$$

Soil-crop nitrogen balance

The mineral nitrogen balance of the soil is the difference between nitrogen added through mineralization and/or fertilizer, and removed by crop uptake and losses. The net rate of change of N in soil (dN/dt in g m^{-2} d^{-1}) is:

$$\left(\frac{\mathrm{dN}}{\mathrm{dt}}\right)_{\mathrm{soil}} = \mathrm{N_{min}} + (\mathrm{QN_{fer}}\,\mathrm{NRF}) - (\mathrm{dNU/dt})$$

where N_{min} is the nitrogen supply through mineralization and biological N fixation, QN_{fer} is the fertilizer nitrogen application rate, NRF is the fertilizer nitrogen recovery fraction (see next section, nitrogen supply from soil) and dNU/dt is the rate of nitrogen uptake by the crop, which is calculated as the minimum of N supply from the soil and the crop demand (see section nitrogen demand).

Nitrogen supply from soil

Mineral nitrogen available for crop uptake originates from three sources: nitrogen present in the soil profile at germination/transplanting, nitrogen from biological fixation and mineralized from soil organic matter during the growing season and nitrogen applied as fertilizer. Under aerobic conditions, indigenous soil nitrogen supply can be reasonably accurately quantified on the basis of soil organic matter content (Sinclair and Amir, 1992). However, in flooded soils, under anaerobic conditions, differences in mineral N-supply among fields or seasons could not be explained on the basis of soil organic carbon, total nitrogen or initial inorganic nitrogen (Cassman et al., 1996; Bouman et al., 2001). Hence, the model does not simulate nitrogen mineralization, but indigenous nitrogen supply is introduced as a site-specific exogenous input. Ten Berge et al. (1997) found indigenous nitrogen supply values for tropical soils in the range of 0.5 to 0.9 kg ha^{-1} d^{-1}. Fertilizer nitrogen available for plant uptake, taking into account possible losses (volatilization, denitrification, and leaching) is included in the model as a variable fraction, the so-called nitrogen recovery fraction, NRF. Nitrogen recovery fraction depends on soil type, growth stage of the crop, fertilizer type and time and mode of application (De Datta, 1986).

Nitrogen demand, uptake and stress

At sub-optimal nitrogen availability in the soil, nitrogen demand of the crop cannot be satisfied, which leads to sub-optimal crop nitrogen concentrations. The concentration below which a crop experiences nitrogen stress is called the *critical* nitrogen concentration. Nitrogen stress results in reduced rates of biomass production and eventually reduced yields. A detailed description of crop nitrogen dynamics is given in Figure 5. The relational diagram shows three reference points of N content in the model, i.e. actual ($NC_{act, pl}$), critical ($NC_{crt, pl}$) and residual ($NC_{res, pl}$). Actual N content is the accumulated N above residual (part of the cell structure). Critical is the N content that corresponds to half of the maximum.

Nitrogen demand

Total crop nitrogen demand is set to the sum of the nitrogen demands of its individual organs (excluding storage organs, for which nitrogen demand is met by translocation from the other organs, i.e. roots, stems and leaves) (Figure 5). Nitrogen demand of

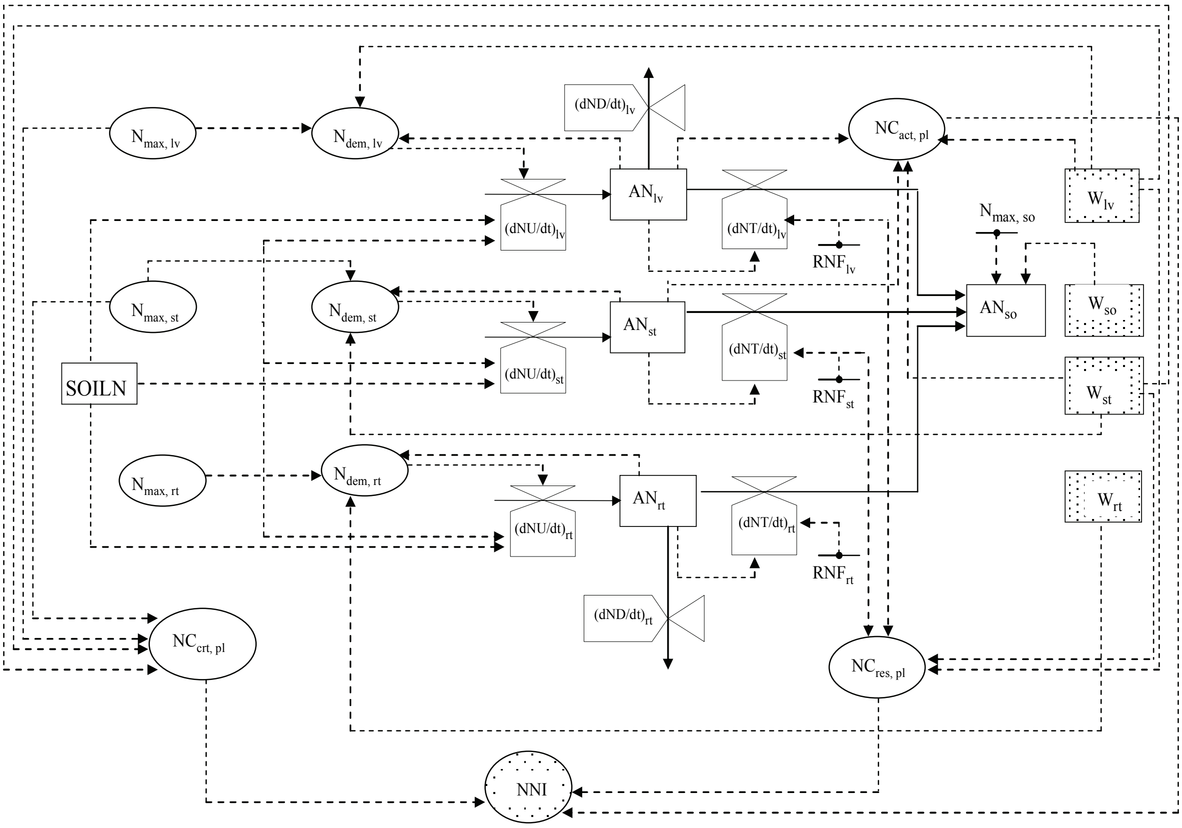

Figure 5. Relational diagram showing nitrogen uptake, translocation and nitrogen content of plant organs in the LINTUL3 model.

Abbrevations used in the diagram: SOILN- available N in soil; $Nmax_{,\ lv}$- maximum nitrogen concentration in leaves; $N_{max,\ st}$-maximum nitrogen concentration in stems; $N_{max,\ rt}$- maximum nitrogen concentration in roots; $N_{dem,\ lv}$- nitrogen demand of leaves; $N_{dem,\ st}$- nitrogen demand of stems; $N_{dem,\ rt}$- nitrogen demand of roots; $(dNU/dt)_{lv}$ - rate of nitrogen uptake in leaves; $(dNU/dt)_{st}$- rate of nitrogen uptake in stems; $(dNU/dt)_{rt}$- rate of nitrogen uptake in roots; $(dND/dt)_{lv}$- rate of nitrogen loss by death of leaves; $(dND/dt)_{rt}$- rate of nitrogen loss by death of roots; $(dNT/dt)_{lv}$- rate of nitrogen translocation from leaves; $(dNT/dt)_{st}$- rate of nitrogen translocation from stems; $(dNT/dt)_{rt}$- rate of nitrogen translocation from roots; RNF_{lv}- residual nitrogen concentration in leaves; RNF_{st}- residual nitrogen concentration in stems; RNF_{rt}- residual nitrogen concentration in roots; AN_{lv}- amount of nitrogen in leaves; AN_{st}- amount of nitrogen in stems; AN_{rt}- amount of nitrogen in roots; AN_{so}- amount of nitrogen in storage organs; $NC_{act,\ pl}$- actual nitrogen concentration in leaves and stems; $NC_{crt,\ pl}$- critical nitrogen concentration in leaves and stems; $NC_{res,\ pl}$- residual nitrogen concentration in leaves and stems; W_{lv}- weight of leaves (green + dead); W_{so}- weight of storage organs; W_{st}- weight of stems; W_{rt}- weight of roots; NNI- nitrogen nutrition index.

Solid lines and dotted lines are indicating material and information flows, respectively, and shaded structures indicate that they are linked to Figure 2.

individual organs (leaves, stems, roots and storage organs) is calculated as the difference between potential and actual organ nitrogen contents. Potential nitrogen content is derived from maximum nitrogen concentration in an organ, defined as a function of canopy development stage (Figure 6) (Drenth et al., 1994). Total N demand (TN_{dem}) of the crop is:

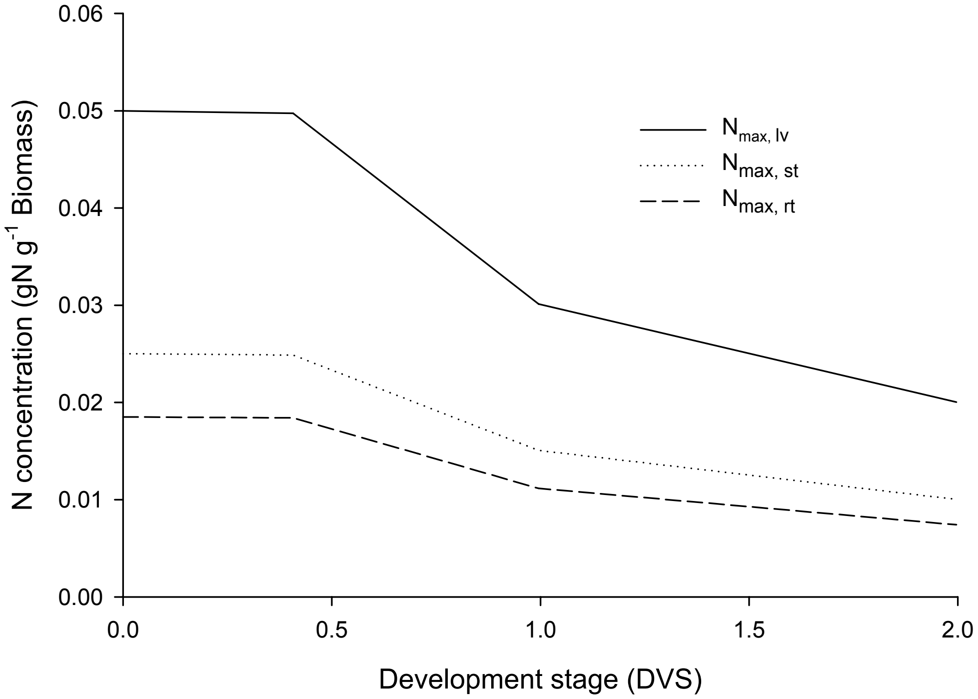

Figure 6. Maximum nitrogen concentration in leaves ($N_{max, lv}$), stem ($N_{max, st}$) and roots ($N_{max, rt}$) as a function of development stage.

$$TN_{dem} = \sum_{i=1}^{n} \left(N_{max,i} \, W_i - AN_i \right)$$

where $N_{max,i}$ is maximum nitrogen concentration of organ i (g g^{-1} biomass), W_i weight of organ i (g biomass m^{-2}), and AN_i actual nitrogen content of organ i (g m^{-2}).

Nitrogen uptake

Nitrogen uptake is determined by crop demand, indigenous soil nitrogen supply and fertilizer application. Nitrogen uptake processes like mass flow and diffusion are not simulated in the model. However, N uptake by the crop is estimated via a simple book keeping approach, similar to that in ORYZA (Bouman et al., 2001). First the crop takes up nitrogen mineralized from indigenous organic matter, and then from fertilizer. Total nitrogen taken up by the crop (dNU/dt) is partitioned (Figure 5) among the different organs in proportion to their demands:

$$\left(\frac{dNU}{dt} \right)_i = (N_{dem, i} \, / \, TN_{dem}) \, (dNU/dt)$$

where $(dNU/dt)_i$, and $N_{dem,\ i}$ are rate of nitrogen uptake (g m^{-2} d^{-1}) and nitrogen demand (g m^{-2} d^{-1}) of organ *i*, respectively.

Nitrogen uptake is assumed to cease at anthesis, as nitrogen content in the vegetative parts hardly increases after anthesis (Groot, 1987; Sinclair and Amir, 1992). Nitrogen demand of the grains is met exclusively by translocation from leaves, stems, and roots after anthesis. Hence, the rate of nitrogen accumulation in the storage organs is determined by their nitrogen demand and total translocatable nitrogen in the crop (Figure 5). Total translocatable nitrogen in the crop equals total nitrogen content of the organs, minus their residual non-transferable nitrogen content, i.e. the nitrogen incorporated in structural crop components. The net rate of change of nitrogen in each of the organs (Figure 5), leaves, stem and roots $(dN/dt)_i$ is:

$$\left(\frac{dN}{dt}\right)_i = \left(\frac{dNU}{dt}\right)_i - \left(\frac{dNT}{dt}\right)_i - \left(\frac{dND}{dt}\right)_i$$

where $(dNU/dt)_i$, $(dNT/dt)_i$ and $(dND/dt)_i$ are the contributions of nitrogen uptake to the organ, translocation and loss of nitrogen due to death of the organ, respectively. It is assumed that the stem does not die and therefore, $(dND/dt)_{stem}$ equals zero.

Nitrogen stress

A crop is assumed to experience N stress at N concentrations below a critical value for unrestricted growth. To quantify crop response to nitrogen shortage, a Nitrogen Nutrition Index (NNI) is defined, ranging from 0 to 1 (Lemaire et al., 1989; van Delden, 2001):

$$NNI = (\text{actual crop [N]}–\text{residual [N]}) / (\text{critical [N]}–\text{residual [N]})$$

Critical crop nitrogen concentration, the lower limit of canopy nitrogen concentration (defined as nitrogen in leaves and stems) required for unrestricted growth, has been set to 50 percent of the maximum nitrogen concentration (Jamieson et al., 1998).

Nitrogen limitation on crop growth

In previous models, effects of nitrogen shortage on crop growth have been incorporated through growth reduction factors, similar to water stress (Jamieson et al., 1998), affecting leaf expansion, leaf senescence, and the rate of photosynthesis per unit area or LUE. Quantification of these effects appeared difficult, because of conflicting reports on effects on LAI and LUE (Green, 1987; Garcia et al., 1988;

Sinclair and Horie, 1989; Jamieson et al., 2000). Two possible crop responses to N shortage can be envisaged (Van Delden, 2001): reduced rate of leaf area expansion while maintaining LUE, or maintaining leaf area expansion and intercepted PAR at a reduced LUE. Theoretical studies and studies under controlled conditions (Sinclair and Horie, 1989) in maize, rice and soybean and field studies in wheat (Green, 1987) have shown higher LUE in crops with higher leaf nitrogen contents. However, field studies by Garcia et al. (1988) have shown that increased nitrogen application resulted in increased light interception in winter wheat due to more rapid leaf expansion. In potato, leaf area expansion was affected by nitrogen deficiency, whereas LUE showed only limited response (Vos and Van der Putten, 1998; Van Delden, 2001). Under field conditions with moderate water and nitrogen stress, LUE will not be affected significantly, whereas under severe stress, such as during a sudden transfer from an optimum nutrient solution to a deficient one, plants may not be able to rapidly modify their morphology, but may reduce LUE (Garcia et al., 1988). Porter (1993) found that in wheat LUE was affected when the ratio of actual to critical nitrogen concentration dropped below a value of 0.3. Morphologically, nitrogen shortage in plants usually leads to thicker leaves, in an attempt to maintain nitrogen concentration per unit leaf area. If leaf nitrogen concentration per unit leaf area decreases, as nitrogen is translocated from the oldest leaves at the bottom of the canopy to new leaves or to grains, leaf life span also decreases (Willington et al., 1983).

In our model, nitrogen stress leads to reduced biomass partitioning to leaves to the benefit of stems, translocation of stem reserves to storage organs, a restriction in leaf area growth and acceleration of leaf senescence. The partitioning factor to leaves ($\mathrm{Pc}_{\mathrm{lv}}$), derived by calibration, is defined as:

$$\mathrm{Pc}_{\mathrm{lv,\,ns}} = \mathrm{Pc}_{\mathrm{lv}}\, e^{-(1-\mathrm{NNI})}$$

where $\mathrm{Pc}_{\mathrm{lv}}$ and $\mathrm{Pc}_{\mathrm{lv,\,ns}}$ are the fractions partitioned to leaves at optimal and sub-optimal nitrogen status, respectively.

After flowering, part of the stem reserves is transferred to the storage organs in response to N stress. The stem reserve fraction translocated, quantified via calibration, increases linearly with N stress.

Leaf area growth is reduced in proportion to NNI:

$$\left(\frac{\mathrm{dGLAI}}{\mathrm{dt}}\right)_{\mathrm{exp}} = \mathrm{LAI}_t\, \mathrm{RL}\, \mathrm{T}_e\, \mathrm{NNI} \qquad \mathrm{DVS} < 0.2 \text{ and } \mathrm{LAI} < 0.75$$

$$\left(\frac{\mathrm{dGLAI}}{\mathrm{dt}}\right)_{\mathrm{sl}} = \left(\frac{\mathrm{dW}}{\mathrm{dt}}\right)_{\mathrm{lv}} \mathrm{S_{la}\,NNI} \qquad \mathrm{DVS} \geq 0.2 \text{ or } \mathrm{LAI} \geq 0.75$$

Death of leaves due to nitrogen stress is added to that due to senescence. Loss of leaf area ($m^2\ m^{-2}\ d^{-1}$) due to nitrogen stress is calculated as:

$$\left(\frac{\mathrm{dDLAI}}{\mathrm{dt}}\right)_{\mathrm{ns}} = \mathrm{LAI\ RDR_{ns}}\ (1 - \mathrm{NNI})$$

where $\mathrm{RDR_{ns}}$ is the maximum relative death rate of LAI due to nitrogen stress.

The corresponding loss of leaf weight is calculated using SLA, the specific leaf area ($m^2\ g^{-1}$):

$$\left(\frac{\mathrm{dDW}}{\mathrm{dt}}\right)_{\mathrm{lv,ns}} = (\mathrm{d\ DLAI/dt})_{\mathrm{ns}}/\mathrm{SLA}$$

Model evaluation

The model was evaluated against data sets (Table 1) of experiments conducted in Asia that also have been used for evaluation of the ORYZA group of models (Drenth et al., 1994; Bouman et al., 2007). Model results are compared graphically to observed data and Root Mean Square Deviation (RMSD[1]) and Average Absolute Deviation (AAD) were calculated for evaluating model performance during calibration and validation.

Calibration

Calibration, the process of adapting model parameters to improve agreement between model results and reality (Van Ittersum et al., 2003), is usually performed in a step-wise manner, starting with the calibration of crop phenology, followed by total biomass production, partitioning and leaf area index. Model parameters (Table 2) were calibrated on the basis of datasets of experiments conducted at the International Rice Research Institute (IRRI), Philippines and at the Central Rice Research Institute

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[1] RMSD $= \left[\frac{\sum_{i=1}^{n}(Y_i - O_i)^2}{n}\right]^{0.5}$; AAD (%) $= \left[\frac{\sum_{i=1}^{n} Abs(Y_i - O_i)}{O_i}\right] \frac{100}{n}$ where Y_i and O_i are simulated and observed values, respectively.

(CRRI), India. The model was first calibrated for non-limiting nitrogen situations with the treatments 180 and 225 kg N ha^{-1} of the dataset IRRI 1992 and subsequently for the nitrogen-limited treatments of IRRI-1991, wet season (WS) and CRRI-1990, dry season (DS).

Heat sums for each cultivar were calculated from observed dates of flowering and maturity and from recorded weather data. For each data set, the model was initialized with observed weights of leaves, stems and roots at transplanting. Light use efficiency values were also calibrated, because of variation in radiation and temperature as explained by Choudhury (2001a), resulting in values of 3.0 (g dry matter MJ^{-1} PAR intercepted) for IR72 at IRRI and 2.7 for IR36 at CRRI. These values refer to totall biomass, including roots, and are comparable to reported values of 2.4 (Kiniry et al.,1989; Mitchell et al., 1998; Kiniry et al., 2001) and 2.0 (Choudhury, 2001b), referring to aboveground biomass. On the basis of a varying root to shoot ratio of 0.5–0.1 over the crop growing period, these values are equivalent to values in the range of 2.2–3.6 g MJ^{-1} for total biomass.

Indigenous soil nitrogen supply, which depends on soil characteristics such as texture and organic matter content, and on management, was calibrated on the basis of the zero N-fertilizer treatments, and was set to 0.05 g N m^{-2} d^{-1}, for both IRRI and CRRI.

Results of calibration

Nitrogen nutrition index values for different treatments in the experiments used for calibration show a clear response to nitrogen application (Figure 7). In the no-fertilizer treatment, the fixed ‘indigenous’ soil N supply is enough to support crop growth without stress up to 20–30 days after transplanting. Subsequent nitrogen demand, associated with radiation-driven growth rates, can only be met by external sources of nitrogen. Split application of N, as in the 225 kg ha^{-1} treatment, covers crop requirements until flowering. The model-calculated aboveground biomass under 180 kg N ha^{-1} is comparable to that under 225 kg N ha^{-1}, as the crop does not experience nitrogen stress until close to flowering time (Figure 7). In the wet season of IRRI91, even though fertilizer application was relatively low (80 and 110 kg N ha^{-1}) compared to IRRI92-DS, crop nitrogen demand could be met almost until flowering. However, the biomass formed was proportionally lower. The low incident radiation in the wet season restricts growth rates and consequently N demand. Results of CRRI90-DS show the effect of N-dose on NNI and biomass formation. Nitrogen nutrition index values show a clear effect of N dose and splits. However, the total aboveground biomass yields were not different for the different fertilizer doses. High average daily

Table 1. Details of datasets used for calibration and validation of LINTUL3.

Data*	Variety	Sowing date	Transplanting date (day of year)	Fertilizer-N(kg ha^{-1})	N-fertilizer splits (kg ha^{-1})	N-fertilizer schedule
			Calibration			
IRRI91-WS†	IR 72	1 Jul, 1990	13 Jul (194)	0	0	no-N
				80	50, 30	Basal††, 31 DAT
				110	30, 30, 20, 30	Basal††, 25, 60, 83 DAT
IRRI92-DS†	IR 72	4 Jan, 1992	16 Jan (16)	0	0	no-N
				180	120, 60	Basal, 18 DAT
				225	60, 60, 60, 45	Basal, 18 DAT, PI, FL
CRRI90-DS	IR 36	18 Dec, 1989	25 Jan (25)	0	0	no-N
				50	25, 12.5, 12.5	Basal, 20, 53 DAT
				100	50, 25, 25	Basal, 20, 53 DAT
				150	75, 37.5, 37.5	Basal, 20, 53 DAT
			Validation			
IRRI92-WS	IR 72	1 Jul, 1992	14 Jul (195)	0	0	no-N
				80	80	Basal
				80	40, 40	Basal, MT
				80	27, 27, 27	Basal, MT, PI
IRRI93-DS	IR 72	14 Jan,1993	25 Jan (25)	0	0	no-N
				100	14.3, 14.3, 14.3, 14.3, 14.3, 14.3, 14.3	weekly interval
				400	57.1, 57.1, 57.1, 57.1, 57.1, 57.1, 57.1	weekly interval
CRRI92-DS	IR 36	8 Jan, 1992	28 Jan (28)	0	0	no-N
				100	100	PI
				100	100	13 DAT
				200	100, 100	13 DAT, PI

*Sources: Drenth et al., 1994; Dash et al., 1994; Wopereis et al., 1994.
†WS: Wet season; DS: Dry season.
†† Basal – at transplanting; PI: Panicle initiation; FL: flowering; MT: maximum tillering; DAT: days after transplanting.

total radiation in CRRI (19.8 MJ m^{-2} d^{-1}) leads to a higher biomass production and leaf area index (about 3) in the initial phase, which may be enough to fully utilize PAR. Therefore, the N stress occurring in the later part of the growing season does not strongly affect crop yield.

Simulated time courses of aboveground biomass, leaf, stem and grain weights, leaf area index and nitrogen concentration in green plant parts for IRRI92-DS show good agreement with observed values, for a range of fertilizer application rates (Figures 8 and 9). Other calibration experiments, showing similar results, are not shown here. Nitrogen concentrations in the green plant parts (leaves and stems) decrease with crop development, even under optimal N-supply, due to dilution as biomass increases

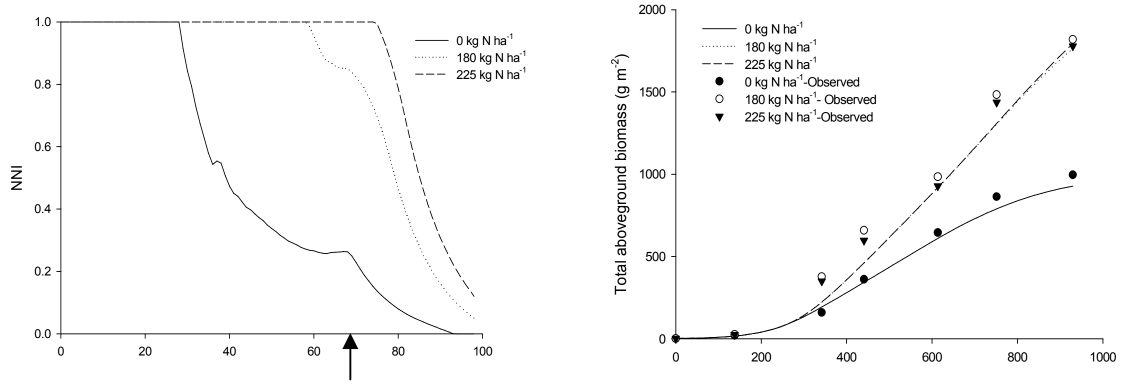
Table 2. Parameters of the LINTUL3 model used for rice.

Parameter description	Values	Units
Crop specific parameters		
Light use efficiency, LUE	2.7-3.0	g MJ^{-1}
Light extinction coefficient, K	0.6	-
Base temperature for crop development, Tb	8.0	°C
Max. relative growth rate of leaf area index, RL	0.0085	(°C d)$^{-1}$
Specific leaf area constant, S_{lac}	0.020	m^2 g^{-1}
Residual N fraction in root, $N_{res, rt}$	0.002	g g^{-1}
Residual N fraction in stem, $N_{res, st}$	0.0015	g g^{-1}
Residual N fraction in leaves, $N_{res, lv}$	0.0040	g g^{-1}
Max. N concentration of stem as fraction of that of leaves, LSNR	0.50	g g^{-1}
Max. N concentration of root as fraction of that of leaves, LRNR	0.37	g g^{-1}
Max. rooting depth, RD_{max}	1.0	m
Max. rate of increase in rooting depth, RRD_{max}	0.010	m d^{-1}
Max. concentration of nitrogen in storage organs, $N_{max, so}$	0.0175	g g^{-1}
Nitrogen translocation from roots to storage organs as a fraction of total amount of nitrogen translocated from leaves and stem to storage organs, FNTRT	0.15	-
Time coefficient for N translocation, TC_{nt}	10.0	d
Critical N, as a fraction of maximum N concentration, FRNX	0.5	-
Relative death rate of leaf area due to N stress, RDR_{ns}	0.02	d^{-1}
Variety specific parameters		
Heat sum for vegetative crop growth, $H_{sum, ant}$	1400-1800	°C d
Heat sum for reproductive crop growth, $H_{sum,mat}$	600-900	°C d

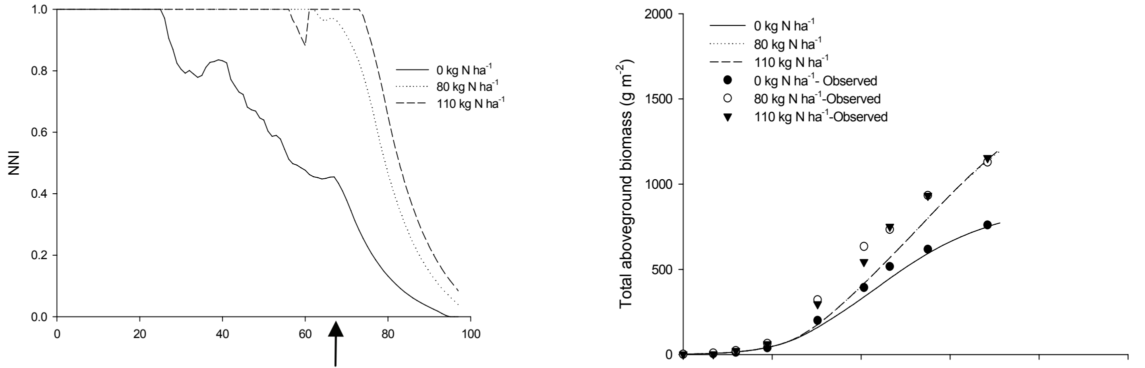
(Figure 9). Data for root biomass were available only for CRRI. The calculated root biomass and root to shoot ratio for CRRI90 data are comparable to the observations (Figure 10), except for the non-fertilized treatment, where root biomass is overestimated, especially in the period 40–80 days after transplanting.

In the calibration data set, agreement between observed and simulated results was closest for IRRI92-DS with an AAD of 21 percent (Table 3). Maximum deviation (30%) of model results compared to the observations was found for CRRI90,

IRRI92-DS



IRRI91-WS



CRRI90-DS

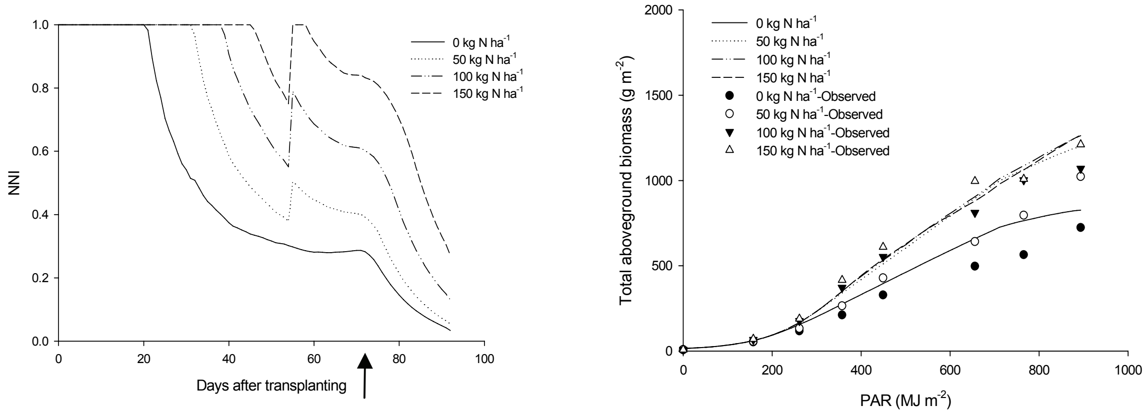
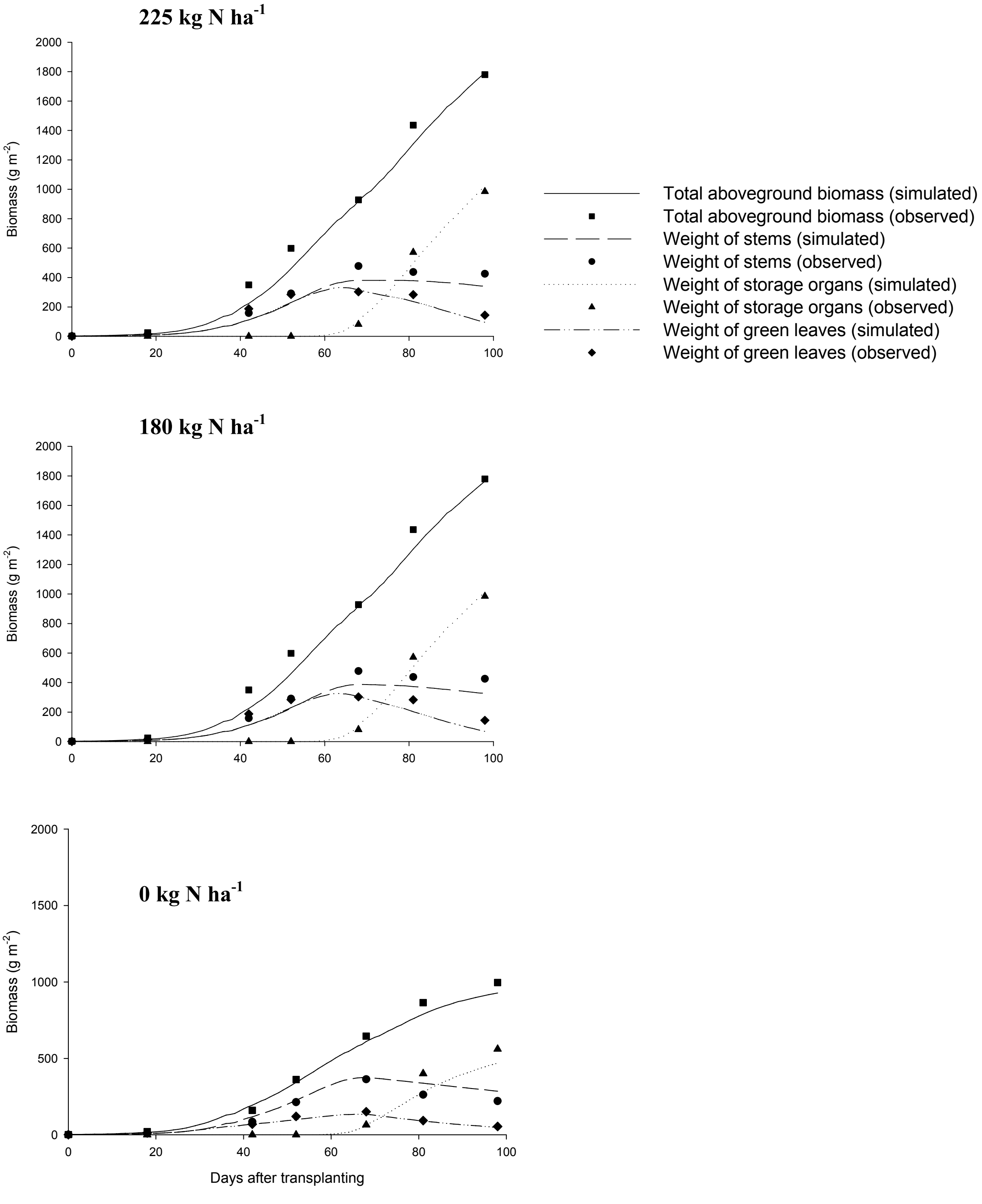


Figure 7. Nitrogen nutrition index as a function of time and total aboveground biomass versus incident PAR for different treatments of different experiments used for calibration (arrows indicate the time of flowering when N uptake also ceases).


225 kg N ha^{-1}

180 kg N ha^{-1}

0 kg N ha^{-1}

Figure 8. Calibration results of simulated and observed aboveground biomass, green leaves, stems, and storage organs for IRRI92-DS, for different fertilizer treatments.

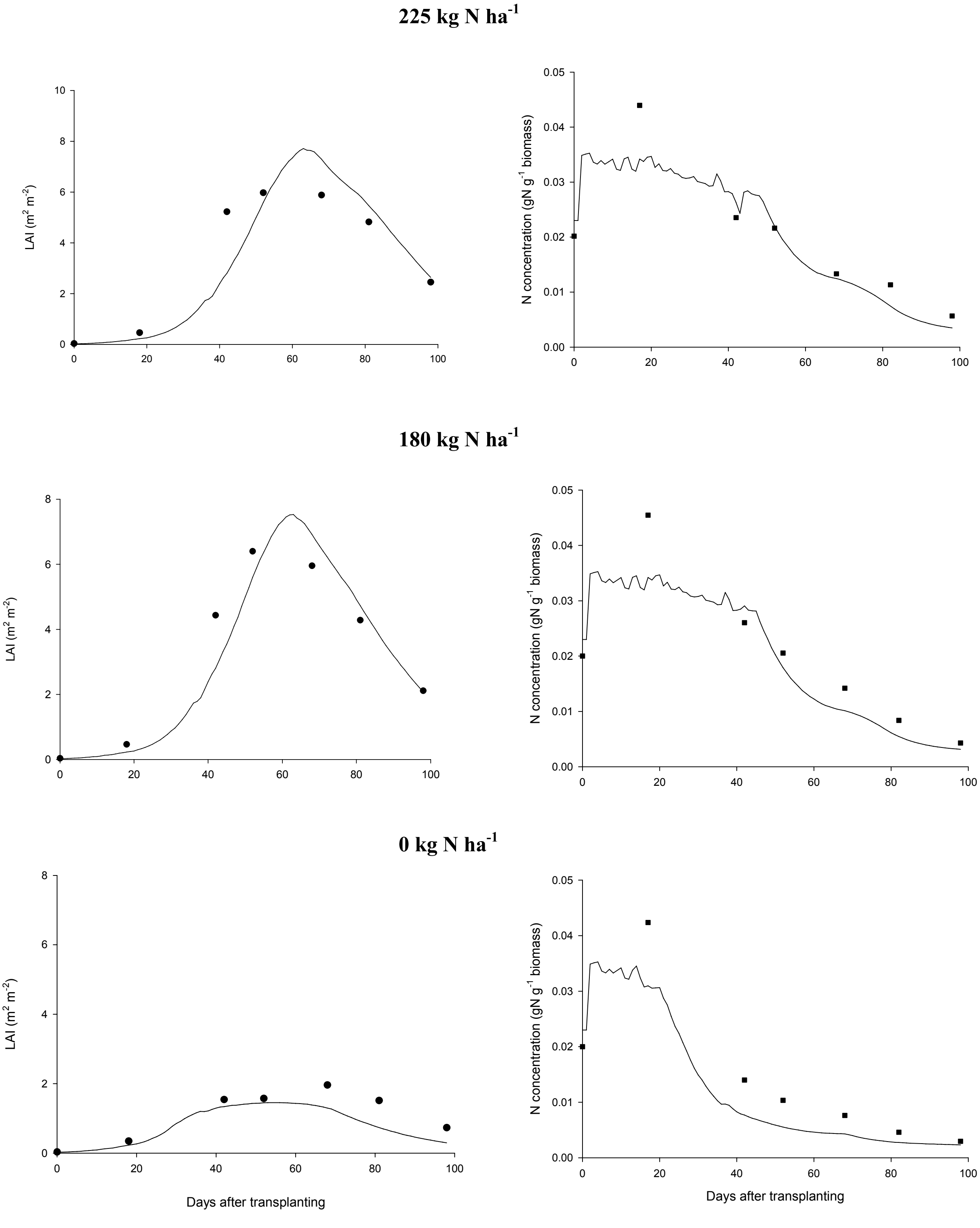


Figure 9. Calibration results of simulated (lines) LAI and N concentration in green plant parts (leaves and stems) in comparison to observed data (symbols) for IRRI92-DS for different fertilizer treatments.

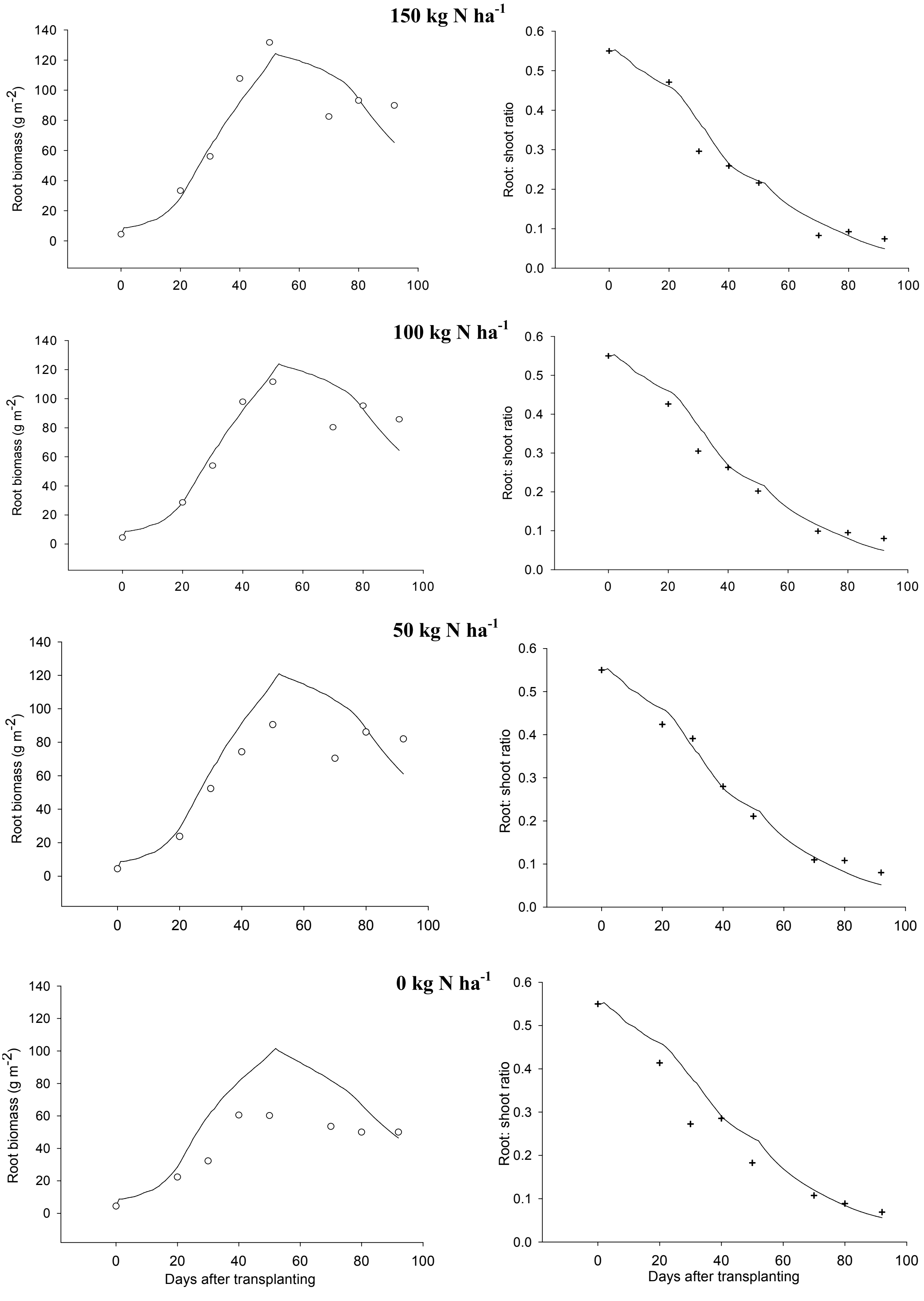
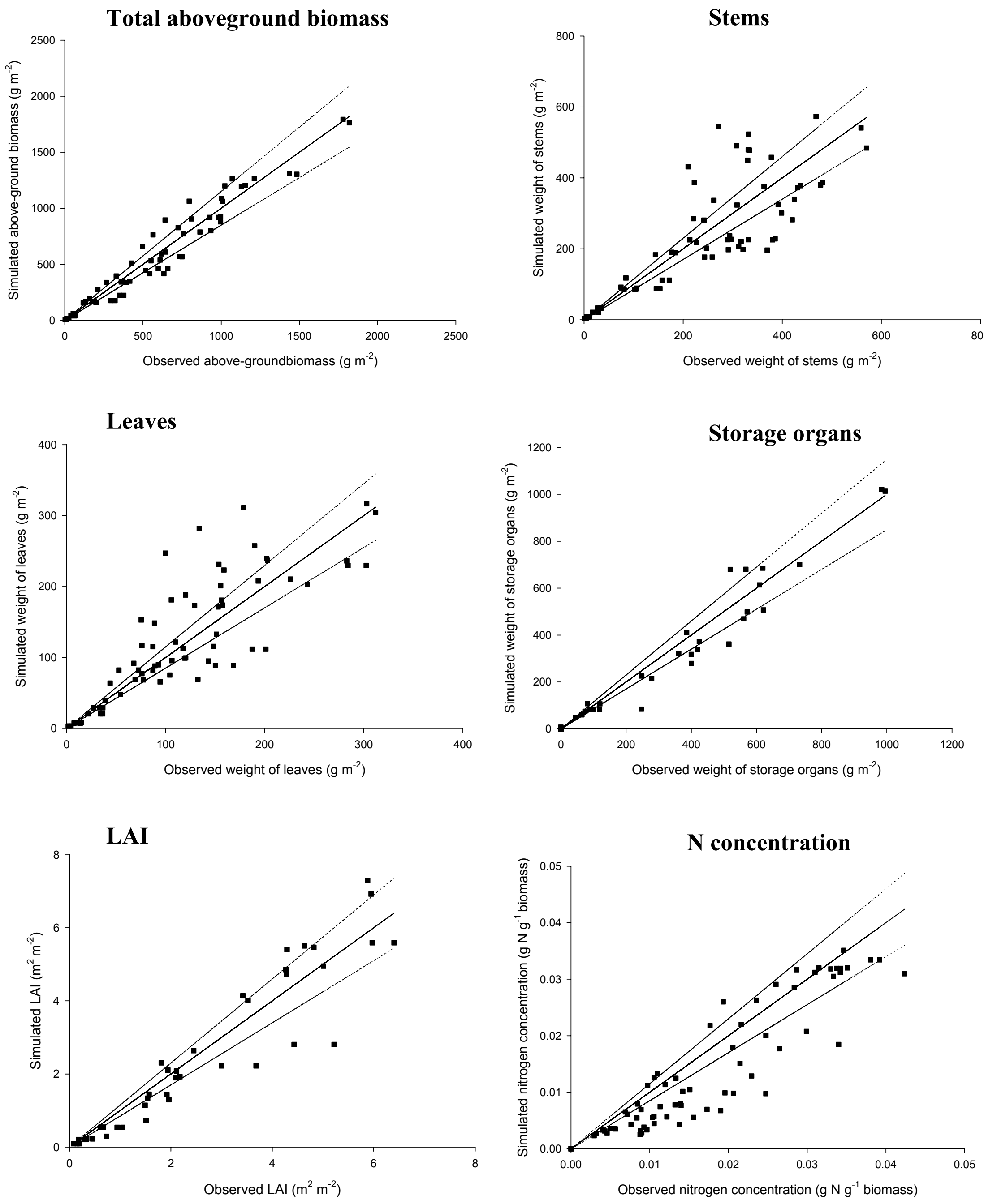


Figure 10. Simulated (lines) and observed (symbols) root biomass and root: shoot ratio for the data set CRRI90-DS, under different fertilizer treatments.



Total aboveground biomass

Stems

Leaves

Storage organs

LAI

N concentration

Figure 11. Comparison of simulated and observed values for weights of total aboveground biomass, stems, leaves, and storage organs and LAI and N concentration of the green parts (leaves and stems) for the whole data set (at various stages of crop growth) used for calibration. Solid lines are 1:1 lines and dotted lines indicate 15 percent deviation from the observed values.

Table 3. Average absolute deviation (AAD) between observed and simulated values for total biomass, stems, roots, leaves, panicles, LAI, and N concentration for different datasets.

Data	N-treatment (kg ha^{-1})	Average absolute deviation (%)							
		Total biomass	Stems	Roots	Leaves	Panicles	LAI	Nitrogen concentration	Average
Calibration									
IRRI92-DS†	0	11	19	-	13	18	33	37	22
	180	22	24	-	30	10	21	23	22
	225	17	21	-	26	16	25	19	21
	Average	17	21		23	15	26	27	21
IRRI91-WS†	0	15	26	-	9	7	16	19	16
	80	26	31	-	28	16	27	15	24
	110	41	58	-	34	19	28	13	32
	Average	28	38	-	24	14	24	16	24
CRRI90-DS	0	26	41	43	41	15	-	61	38
	50	25	31	24	59	7	-	48	32
	100	9	25	13	38	24	-	33	24
	150	10	25	16	30	33	-	31	24
	Average	17	31	24	42	20	-	44	30
Validation									
IRRI92-WS	0	7	19	-	18	3	34	68	25
	80	21	28	-	30	41	21	57	33
	80	21	27	-	23	41	30	52	32
	80	17	18	-	17	44	26	53	29
	Average	16	23	-	22	32	-	58	30
IRRI93-DS	0	33	49	-	12	34	45	-	35
	100	53	41	-	58	114	77	-	68
	400	21	28	-	19	61	26	-	31
	Average	36	39	-	30	70	49		45
CRRI92-DS	0	15	14	43	18	49	-	46	31
	100	29	36	37	40	37	-	33	36
	100	9	14	33	22	39	-	29	24
	200	29	34	29	33	43	-	19	31
	Average	20	25	36	28	42	-	32	30

† WS: Wet season; DS: Dry season.

especially for the situations without N fertilizer (38%; Table 3). Comparing model results and observed data for all datasets used in the calibration (Figure 11) shows that calculated total biomass values are mostly within ± 15% of the observed values, with an average deviation of 21 percent (Table 4). Stem and leaf weights are relatively more scattered than total aboveground biomass and storage organs, while nitrogen concentrations are slightly underestimated (Figure 11). In terms of absolute values, the model showed a RMSD of 102 and 89 g m^{-2} (Table 4) for total aboveground biomass and stem weight, respectively. The values for leaves and storage organs are 47 and 52 g m^{-2}, respectively. Following calibration, showing satisfactory agreement with the observations in terms of biomass, LAI and N content under a range of fertilizer treatments, the model is validated with independent data sets.

Validation

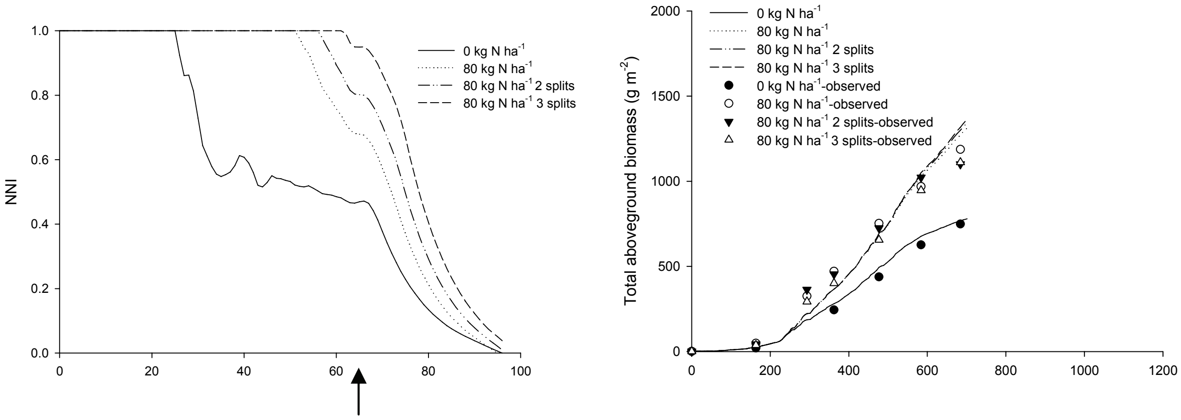
Independent data sets of experiments conducted in the wet season of 1992, and the dry seasons of 1993 at IRRI and of 1992 at CRRI, for fertilizer nitrogen treatments ranging from 0–400 kg N ha^{-1} were used in model validation.

Results of validation

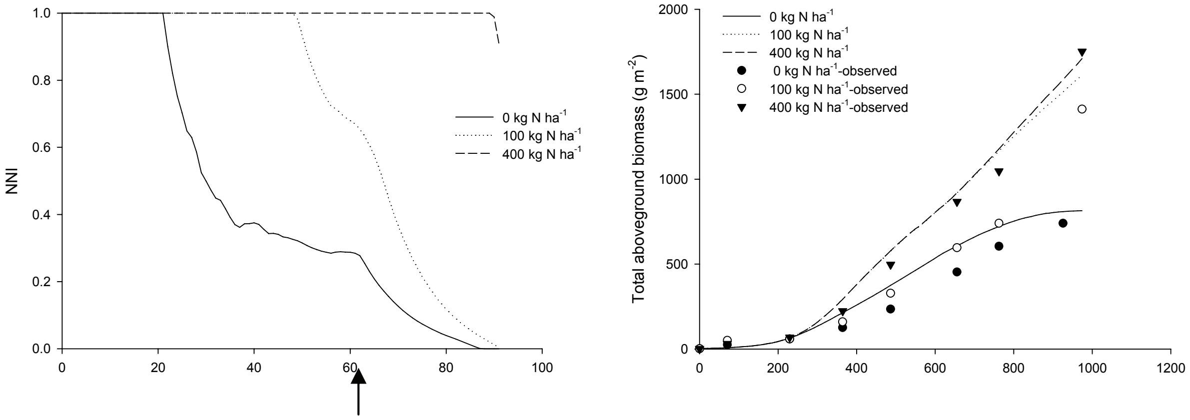
Simulated number of days to flowering matched the observed value (67 DAT) for the IRRI 1992 wet season, whereas maturity (95 DAT) took two more days in the model. In 1993, model-simulated flowering was 6 days early (63 DAT), whereas days to maturity (92 DAT) was exactly reproduced. For CRRI92, number of days to flowering and maturity was overestimated by 7 and 8, respectively. Phenology, in terms of number of days to flowering and maturity for the entire dataset was estimated with a RMSD of 5.4 and 5 days, respectively (Table 4).

Results of IRRI92-WS show the effect of split application of a given fertilizer dose on crop growth and yield (Figure 12). Splits of 80 kg ha^{-1} as basal dressing, at tillering and at panicle initiation show hardly any increase in total aboveground biomass compared to a single basal application. Observed values show a marginally higher total aboveground biomass for a single basal application, compared to the three splits. A higher dose of N as basal application may lead to higher N uptake, which can be stored for later growth (Shangguan et al., 2004). Maximum nitrogen concentration in the model, which is double the critical N concentration, may allow luxury N uptake in the crop. However, for IRRI93-DS, application of 400 kg N ha^{-1} does not increase total biomass in proportion to N-uptake (Figure 12). A similar biomass was also simulated with 100 kg N ha^{-1} in seven splits, synchronized with nitrogen demand. Model results

IRRI92 WS



IRRI93 DS



CRRI92 DS

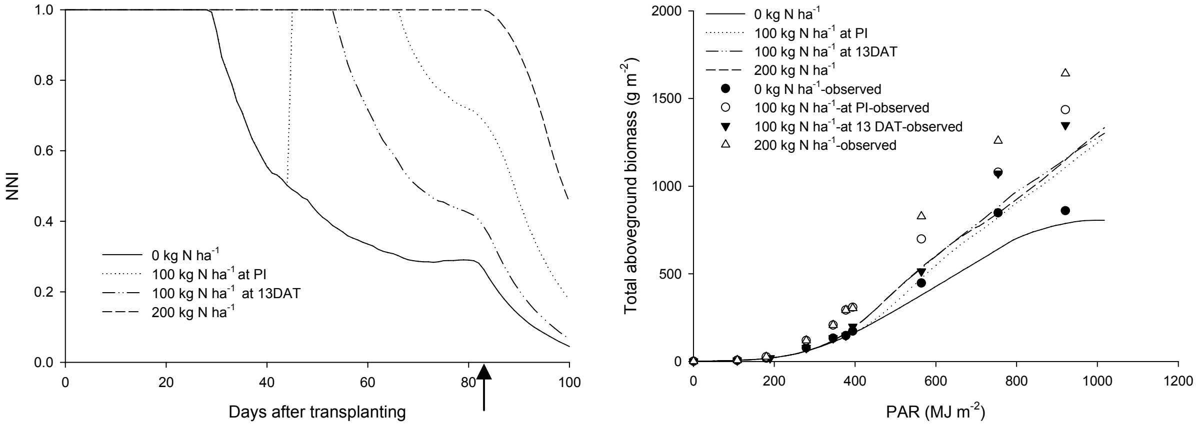
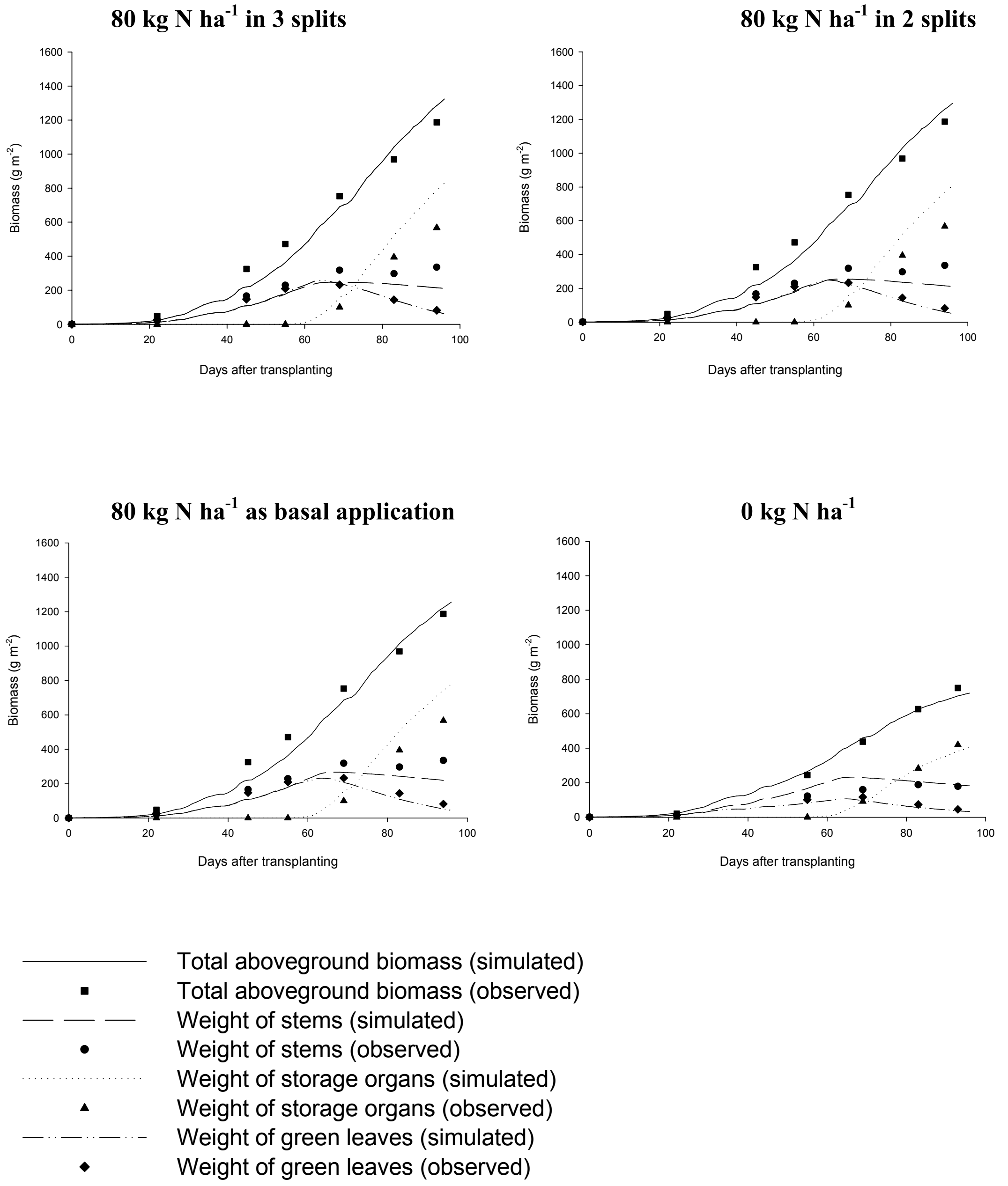


Figure 12. Time course of nitrogen nutrition index (NNI) and the relation (simulated and observed) between total aboveground biomass and incident PAR for different treatments of different experiments used for validation (arrows indicate the time of flowering when N uptake ceases).



80 kg N ha^{-1} in 3 splits

80 kg N ha^{-1} in 2 splits

80 kg N ha^{-1} as basal application

0 kg N ha^{-1}

Figure 13. Simulated and observed weight of total aboveground biomass, green leaves, stems and storage organs for data set IRRI92-WS in the validation for different fertilizer treatments.

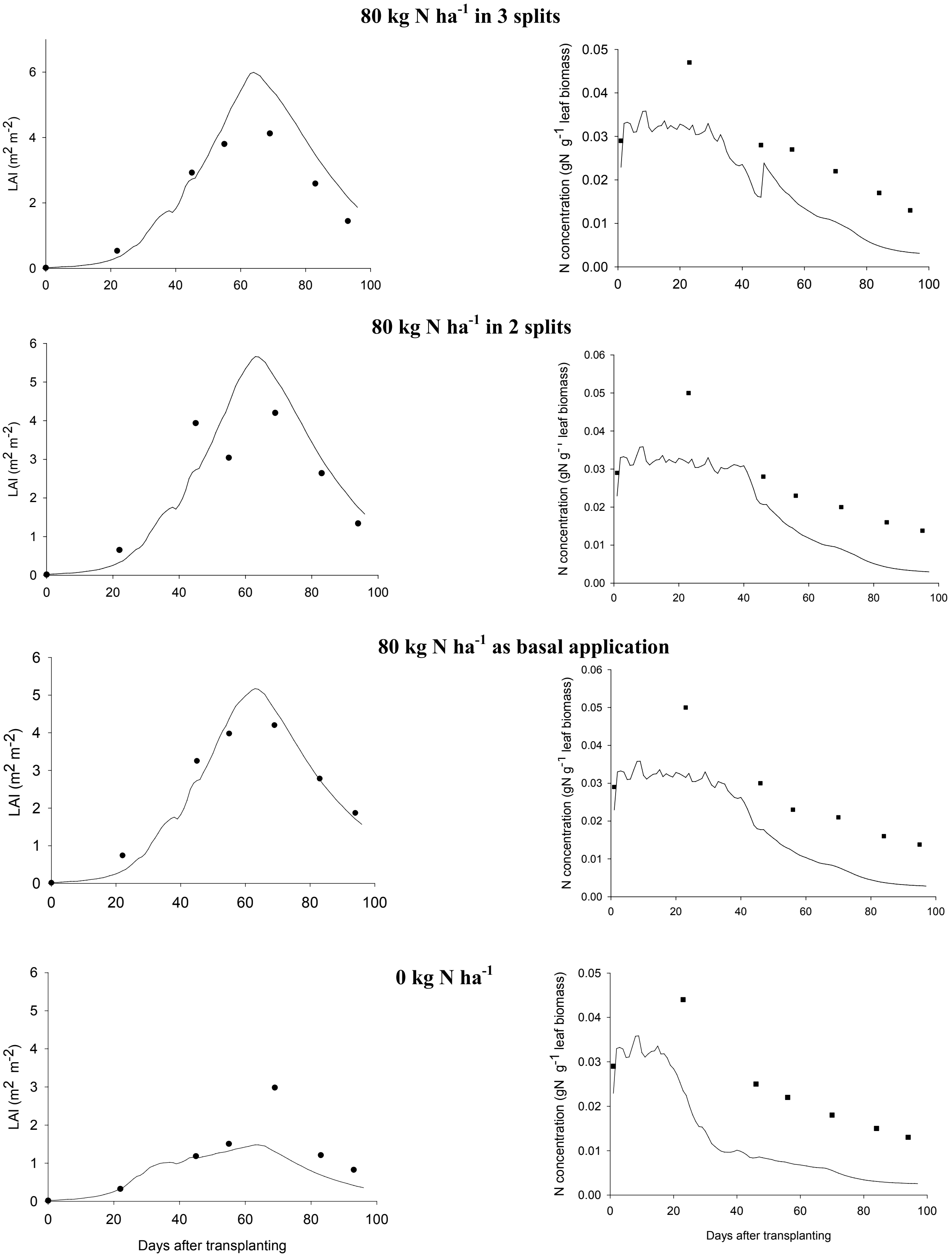
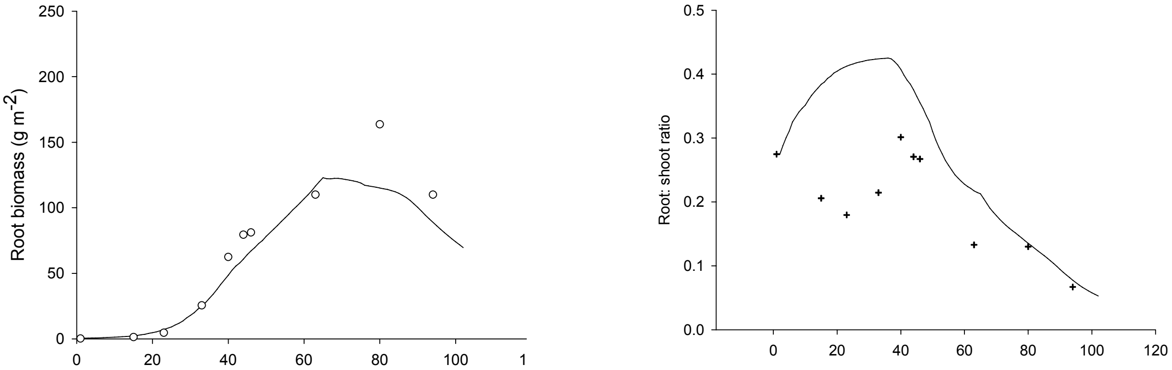
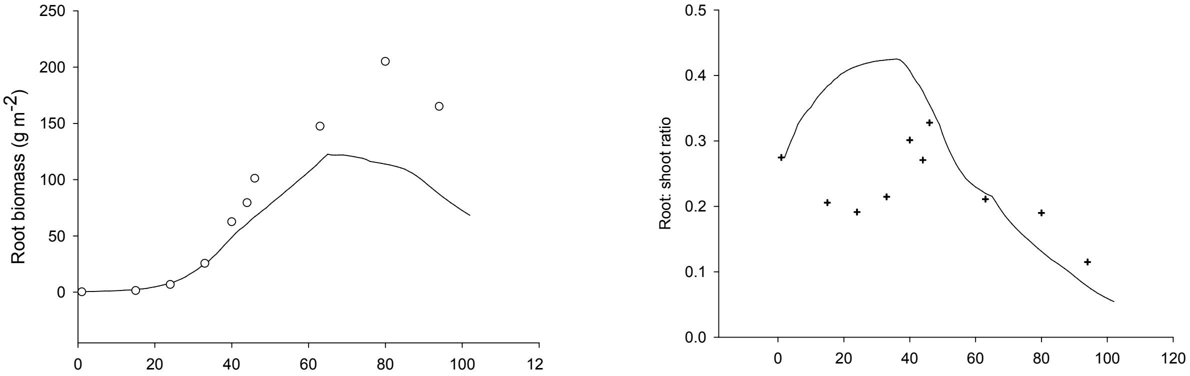


Figure 14. Simulated (lines) and observed (symbols) LAI and nitrogen concentration in leaves for the dataset IRRI92-WS in the validation for different fertilizer treatments.

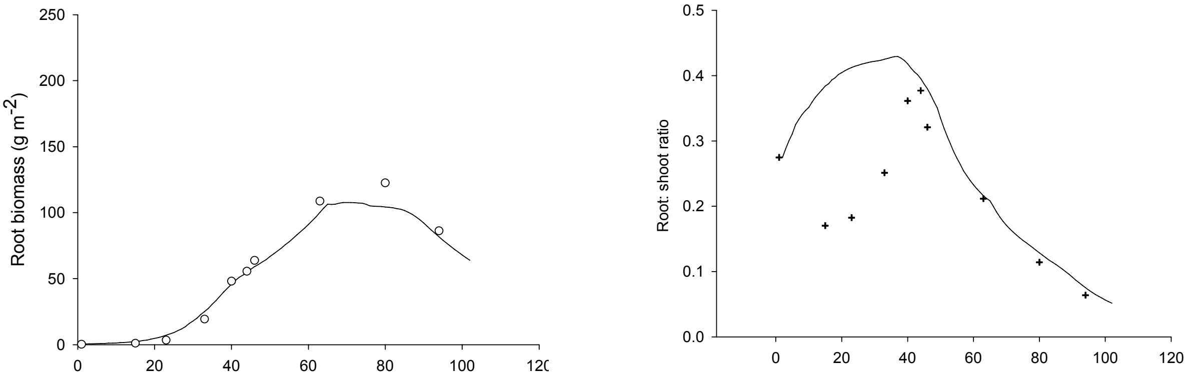
200 kg N ha^{-1}



100 kg N ha^{-1} at 13 days after transplanting



100 kg N ha^{-1} at panicle initiation



0 kg N ha^{-1}

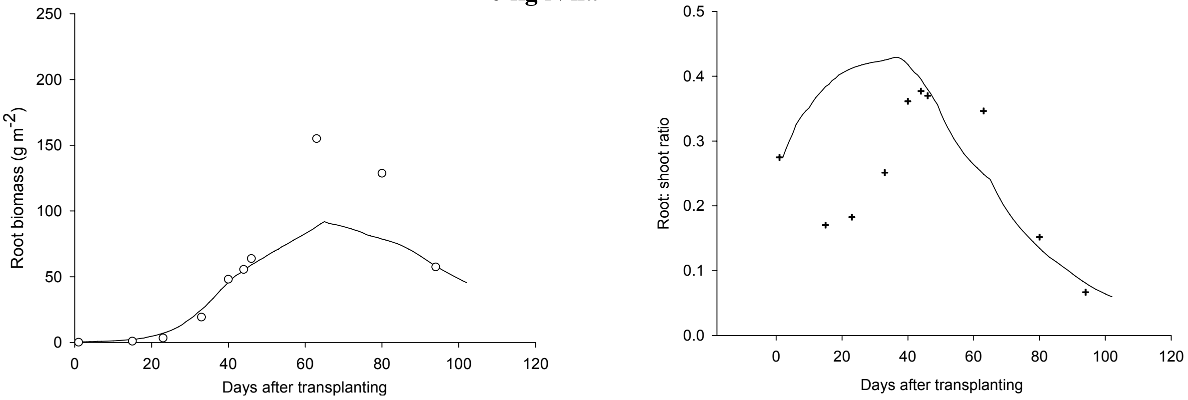


Figure 15. Simulated (lines) and observed (symbols) root biomass and root: shoot ratio for the data set CRRI92-DS, under different fertilizer treatments.

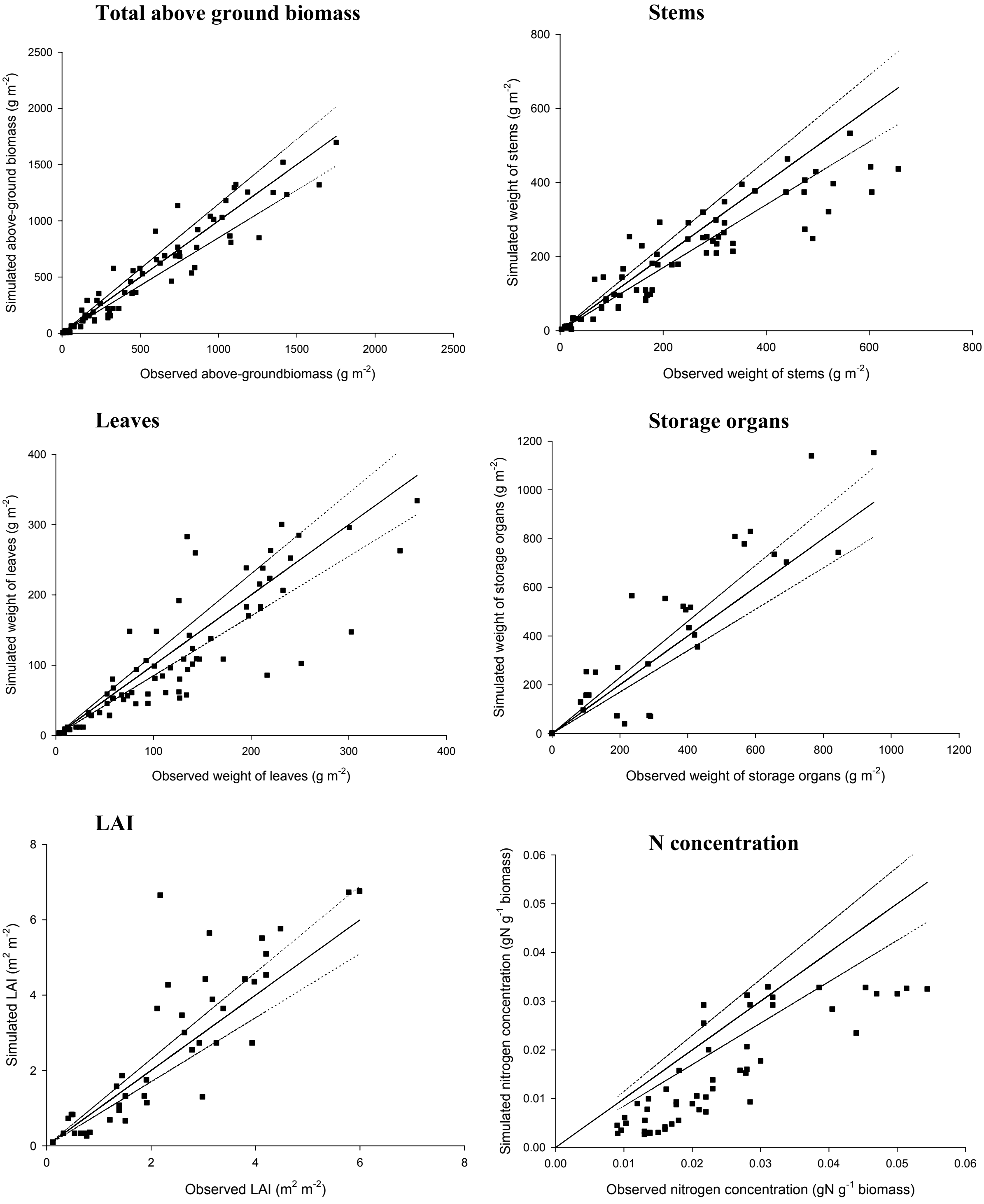


Figure 16. Comparison of simulated and observed values for weights of total aboveground biomass, stems, leaves, and storage organs and LAI and N concentration of the green parts (leaves and stems) for the whole data set (at various stages of crop growth) used for validation. Solid lines are 1:1 lines and dotted lines indicate 15 percent deviation from the observed values.

for CRRI92-DS with N application at the rate of 100 kg ha^{-1} at 13 DAT and at PI do not show much difference in biomass production, whereas observed values clearly show a higher biomass for application at PI, which is the most critical stage for nitrogen application in rice.

Model results of biomass distribution and LAI correspond well with observed results for IRRI92-WS (Figures 13 and 14), including the absence of effects of split application. Calculated root biomass is slightly too low (Figure 15), especially without fertilizer application. In the validation set, model results show minimum deviation (30%) for IRRI92-WS and CRRI92-DS, and maximum deviation for IRRI93-DS (45%; Table 3). Storage organs show a wider spread than in the calibration set (Figure 16, Table 4), while stem weights show less scatter (Table 4).

Discussion and conclusions

LINTUL-3 combines the essential crop growth processes as described in LINTUL-1 and LINTUL-2 with the major N processes described in ORYZA 2000 (Bouman and Van Laar, 2006). The nitrogen part of the model describes total N demand of the crop, N supply from the soil and N stress. The latter, expressed in NNI, affects crop performance mainly through restricted leaf growth and increased translocation of stem reserves to storage organs (Shi et al., 1996). Nitrogen supply influences dry matter production and its partitioning within the crop (Lloyd and Taylor, 1994; Reynolds and Chen, 1996; Bannayan et al., 2004). Bannayan et al. (2004) reported that the model simulations using ORYZA 2000 overestimated leaf weight and LAI since biomass partitioning is not affected by N stress. However, LINTUL-3 needs to be validated more extensively under diverse environmental conditions to increase insight in the exact response of these crop characteristics to N stress.

Model performance in general agreed well with the observations. The model responded similarly to the observations to increasing fertilizer doses, i.e with higher biomass production, LAI and N concentration, the magnitude depending on amount, timing and number of splits. Simulated total aboveground biomass was more accurate than weights of individual crop components. The model results show that the effect of N stress on dry matter production is well simulated, whereas that on partitioning and translocation from stem reserves needs to be further tested.

The model does not simulate the flooded conditions typical for the majority of rice systems, but assumes the soil to be continuously saturated. For representation of the typical paddy rice system, the model needs to be extended to include the effects of

Table 4. Root mean square deviation (RMSD) and average absolute deviation (AAD, %) between observed and simulated values for phenology, biomass components, LAI and nitrogen concentration for the whole dataset used for calibration and validation.

	Calibration		Validation	
	RMSD	AAD	RMSD	AAD
Flowering (d)	0.6	0.5	5.4	6.0
Maturity (d)	1.7	1.1	5.0	3.5
Aboveground biomass (g m^{-2})	102	21	130	23
Weight of stem (g m^{-2})	89	31	76	28
Weight of root (g m^{-2})	19	24	30	36
Weight of leaves (g m^{-2})	47	31	47	27
Weight of storage organs (g m^{-2})	52	17	99	47
LAI (m^2 leaf m^{-2} surface area)	0.7	25	1.1	38
N concentration (g N g^{-1} biomass)	0.006	30	0.009	42

puddling and standing water on other soil water processes such as percolation, drainage and runoff. In the current model, soil N processes are not described in detail, but represented by exogenously defined values for indigenous nitrogen supply and fertilizer-N recovery that are site- and season-specific. Therefore, soil moisture does not have a direct effect on nitrogen dynamics. Indigenous N supply representing the contribution from mineralization of soil organic nitrogen, irrigation and rain water, and biological N-fixation was derived by model calibration for each particular site. Though this avoids ambiguity related to the variability in nitrogen availability in flooded rice soils, development of a process-based approach would allow more independent testing of the model.

To conclude, a simple model such as LINTUL, extended with moderately detailed nitrogen processes, does satisfactorily describe the processes for water- and nitrogen-limited growth of rice, provided sufficient(ly detailed) data are available for its calibration.

References

Bannayan, M., Kobayashi, K., Kim, H.Y., Lieffering, M., Okada, M. and Miura, S., 2004. Modeling the interactive effects of atmospheric CO_2 and N on rice growth and yield. Field Crops Research 93, 237-251.

Bouman, B.A.M. and Van Laar, H.H., 2006. Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions. Agricultural Systems 87, 249-273.

Bouman, B.A.M., Humphreys, E., Tuong, T.P. and Barker, R., 2007. Rice and Water. Advances in Agronomy 92, 187-237.

Bouman, B.A.M., Kropff, M.J., Tuong, T.P., Wopereis, M.C.S., Ten Berge, H.F.M. and Van Laar, H.H., 2001. ORYZA2000: modeling lowland rice. International Rice Research Institute, Los Baños, Philippines and Wageningen University and Research centre, Wageningen, The Netherlands, 235 pp.

Cassman, K.G., Dobermann, A., Cruz, P.C.S., Gines, G.C., Samson, M.I., Descalsota, J.P., Alcantara, J.M., Dizon, M.A. and Olk, D.C., 1996. Soil organic matter and the indigenous nitrogen supply of intensive irrigated rice systems in the tropics. Plant and Soil 182, 267-278.

Choudhury, B.J., 2001a. Estimating gross photosynthesis using satellite and ancillary data: approach and preliminary results. Remote Sensing of Environment 75, 1-21.

Choudhury, B.J., 2001b. Modeling radiation- and carbon-use efficiencies of maize, sorghum, and rice. Agricultural and Forest Meteorology 106, 317-330.

Dash, R.N., Rao, K.S., and Nayak, S.K., 1994. Growth, yield and uptake of nitrogen by irrigated rice as affected by timing of fertilizer application. In: Nitrogen Economy of irrigated rice: field and simulation studies. SARP Research Proceedings, CABO-TT, Wageningen, The Netherlands. pp. 1-13.

De Datta, S.K., 1986. Improving nitrogen fertilizer efficiency in lowland rice in tropical Asia. Fertilizer Research 9, 171-186.

Drenth, H., Ten Berge, H.F.M. and Riethoven, J.J.M., 1994. ORYZA simulation modules for potential and nitrogen limited rice production. In: ORYZA simulation modules for potential and nitrogen limited rice production. SARP Research Proceedings, CABO-TT, Wageningen, The Netherlands. 223 pp.

Farré, I., Van Oijen, M., Leffelaar, P.A. and Faci, J.M., 2000. Analysis of maize growth for different irrigation strategies in northeastern Spain. European Journal of Agronomy 12, 225-238.

Gallagher, J.N. and Biscoe, P.V., 1978. Radiation absorption, growth and yield of cereals. Journal of Agricultural Science 91, 47-60.

Garcia, R., Kanemasu, E.T., Blad, B.L., Bauer, A., Hatfield, J.L., Major, D.J., Reginato, R.J. and Hubbard, K.G., 1988. Interception and use efficiency of light in winter wheat under different nitrogen regimes. Agricultural and Forest Meteorology 44, 175-186.

Gastal, F. and Lemaire, G., 2002. N uptake and distribution in crops: an agronomical and ecophysiological perspective. Journal of Experimental Botany 53, 789-799.

Goudriaan, J. and Van Laar, H.H., 1994. Modelling potential crop growth processes: textbook with exercises. Kluwer Academic Publishers, Dordrecht, The Netherlands, 238 pp.

Grace, J., Lloyd, J., McIntyre, J., Miranda, A., Meir, P., Miranda, H., Moncrieff, J., Massheder, J., Wright, I. and Gash, J., 1995. Fluxes of carbon-dioxide and water-vapor over an undisturbed tropical forest in south-west Amazonia. Global Change Biology 1, 1-12.

Green, C.F., 1987. Nitrogen nutrition and wheat growth in relation to absorbed solar radiation. Agricultural and Forest Meteorology 41, 207-248.

Groot, J.J.R., 1987. Simulation of nitrogen balance in a system of winter wheat and soil. Simulation Reports CABO-TT, No. 13, Wageningen, The Netherlands, 69 pp.

Habekotté, B., 1997. Description, parameterization and user guide of LINTUL-BRASNAP 1.1. A crop growth model of winter oilseed rape (*Brassica napus* L.). Quantitative Approaches in Systems Analysis No. 9, Wageningen Agricultural University, Wageningen, The Netherlands, 40 pp.

Jamieson, P.D., Semenov, M.A., Brooking, I.R. and Francis, G.S., 1998. Sirius: a mechanistic model of wheat response to environmental variation. European Journal of Agronomy 8, 161-179.

Jamieson, P.D., Berntsen, J., Ewert, F., Kimball, B.A., Olesen, J.E., Pinter, P.J., Jr., Porter, J.R. and Semenov, M.A., 2000. Modelling CO_2 effects on wheat with varying nitrogen supplies. Agriculture, Ecosystems and Environment 82, 27-37.

Kiniry, J.R., McCauley, G., Xie, Y. and Arnold, J.G., 2001. Rice parameters describing crop performance of four U.S. cultivars. Agronomy Journal 93, 1354-1361.

Kiniry, J.R., Jones, C.A., O'Toole, J.C., Blanchet, R., Cabelguenne, M. and Spanel, D.A., 1989. Radiation-use efficiency in biomass accumulation prior to grain filling for five grain crop species. Field Crops Research 20, 51-64.

Lemaire, G., Gastal, F. and Salette, J., 1989. Analysis of the effect of nitrogen nutrition on dry matter yield of a sward by reference to potential yield and optimum nitrogen content. Proceedings of 16th International Grassland Congress, 4-11 October, Nice, France.

Lloyd, J. and Taylor, J.A., 1994. On the temperature dependence of soil respiration. Functional Ecology 8, 315-323.

Mitchell, P.L., Sheehy, J.E. and Woodward, F.I., 1998. Potential yields and the efficiency of radiation use in rice. IRRI Discussion Paper Series 32, IRRI, Los Baños, Philippines.

Monteith, J.L., 1977. Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 281, 277-294.

Monteith, J.L., 1990. Conservative behaviour in the response of crops to water and light. In: Rabbinge, R., Goudriaan, J., Van Keulen, H., Penning de Vries, F. W. T. and Van Laar, H. H. (Eds.) Theoretical production ecology: reflections and prospects. Pudoc, Wageningen, The Netherlands, pp. 3-16.

Monteith, J.L. and Unsworth, M.H., 1990. Principles of environmental physics. Edward Arnold, London, 291 pp.

Muchow, R.C., 1990. Effect of leaf nitrogen and water regime on the photosynthetic capacity of kenaf (*Hibiscus cannabinus* L.) under field conditions. Australian Journal of Agricultural Research 41, 845-852.

Novoa, R. and Loomis, R.S., 1981. Nitrogen and plant production. Plant and Soil 58, 177-204.

Porter, J.R., 1993. AFRCWHEAT2: A model of the growth and development of wheat incorporating responses to water and nitrogen. European Journal of Agronomy 2, 69-82.

Reynolds, J. and Chen, J., 1996. Modelling whole-plant allocation in relation to carbon and nitrogen supply: Coordination versus optimization: Opinion. Plant and Soil 185, 65-74.

Rosati, A. and DeJong, T.M., 2003. Estimating photosynthetic radiation use efficiency using incident light and photosynthesis of individual leaves. Annals of Botany 91, 869-877.

Ruimy, A., Jarvis, P.G., Baldocchi, D.D. and Saugier, B., 1995. CO_2 fluxes over plant canopies and solar radiation: a review. Advances in Ecological Research 26, 1-68.

Schapendonk, A.H.C.M., Stol, W., Van Kraalingen, D.W.G. and Bouman, B.A.M., 1998. LINGRA, a sink/source model to simulate grassland productivity in Europe. European Journal of Agronomy 9, 87-100.

Shangguan, Z.P., Shao, M.A., Ren, S.J., Zhang, L.M. and Xue, Q., 2004. Effect of nitrogen on root and shoot relations and gas exchange in winter wheat. Botanical Bulletin of Academia Sinica 45, 49-54.

Shi, Q., Pan, X., Zhong, X., Xu, Y., Cheng, Y. and Zheng, X., 1996. Effects of N on source-sink relations in rice. In: Aggarwal, P. K., Lansigan, F. P., Thiyagarajan, T. M. and Rubia, E. G. (Eds.) Towards integration of simulation models in rice research. SARP Research Proceedings, International Rice Research Institute, Los Baños, Philippines and DLO-Research Institute for Agrobiology and Soil Fertility, Wageningen, The Netherlands, 193 pp.

Sinclair, T.R., 1991. Predicting carbon assimilation and crop radiation-use efficiency dependence on leaf nitrogen content. In: Boote, K. J. and Loomis, R. S. (Eds.) Modeling crop photosynthesis-from biochemistry to canopy. CSSA Special Publication 19, American Society of Agronomy and Crop Science Society of America, Madison, WI, USA, pp. 75-94.

Sinclair, T.R. and Horie, T., 1989. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: a review. Crop Science 29, 90-98.

Sinclair, T.R. and Amir, J., 1992. A model to assess nitrogen limitations on the growth and yield of spring wheat. Field Crops Research 30, 63-78.

Sinclair, T.R. and Muchow, R.C., 1999. Radiation use efficiency. Advances in Agronomy 65, 215-265.

Spitters, C.J.T., 1987. An analysis of variation in yield among potato cultivars in terms of light absorption, light utilization and dry matter partitioning. Acta Horticulturae 214, 71-84.

Spitters, C.J.T., 1990. Crop growth models: their usefulness and limitations. Acta Horticulturae 267, 349-368.

Spitters, C.J.T. and Schapendonk, A.H.C.M., 1990. Evaluation of breeding strategies for drought tolerance in potato by means of crop growth simulation. Plant and Soil 123, 193-203.

Ten Berge, H.F.M., Thiyagarajan, T.M., Shi, Q., Wopereis, M.C.S., Drenth, H. and Jansen, M.J.W., 1997. Numerical optimization of nitrogen application to rice. Part I. Description of MANAGE-N. Field Crops Research 51, 29-42.

Van Delden, A., 2001. Yielding ability and weed suppression of potato and wheat under organic nitrogen management. Ph.D. Thesis, Wageningen Agricultural University, Wageningen, The Netherlands, 197 pp.

Van Ittersum, M.K., Leffelaar, P.A., Van Keulen, H., Kropff, M.J., Bastiaans, L. and Goudriaan, J., 2003. On approaches and applications of the Wageningen crop models. European Journal of Agronomy 18, 201-234.

Van Keulen, H., Goudriaan, J. and Seligman, N.G., 1988. Modelling the effects of nitrogen on canopy development and crop growth. In: Russel, G., Marshall, B. and Jarvis, P. G. (Eds.) Plant canopies: Their Growth, Form and Function. Cambridge University Press, Cambridge, UK, pp. 83-104.

Van Oijen, M., 1992. Evaluation of breeding strategies for resistance and tolerance to late blight in potato by means of simulation. Netherlands Journal of Plant Pathology 98, 3-11.

Vergara, B.S. and Chang, T.T., 1985. The flowering response of the rice plant to photoperiod - a review of the literature. International Rice Research Institute, Los Baños, Philippines, 61 pp.

Vos, J. and Van der Putten, P.E.L., 1998. Effect of nitrogen supply on leaf growth, leaf nitrogen economy and photosynthetic capacity in potato. Field Crops Research 59, 63-72.

Willington, V.B.A., Horner, S.E., Martin, T.D. and Biscoe, P.V., 1983. Growth and development of winter wheat. Brooms Barn Experimental Station, Brooms Barn, UK, 43 pp.

Wopereis, M.C.S., Ten Berge, H.F.M., Maligaya, A.R., Kropff, M.J, Aquino, S.T. and Kirk, G.J.D, 1994. In: Nitrogen Economy of irrigated rice: field and simulation studies. SARP Research Proceedings, CABO-TT, Wageningen, The Netherlands. pp.108-129.

Wormer, T.M., 1954. The influence of light intensity on the photoperiodical behaviour of the rice plant. Netherlands of Journal of Agricultural Sciences 2, 48-49.

CHAPTER 5

Long-term dynamics of soil C and N in intensive rice-based cropping systems of the Indo-Gangetic Plains (IGP): A modeling approach

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Abstract

We describe a summary model for the dynamics of carbon and nitrogen under varying weather, crop and soil conditions to investigate the role of soil organic matter in yield formation in rice-based cropping systems of the Indo-Gangetic Plains (IGP). The model consists of three modules: a soil organic matter (SOM) module, a soil (SOIL) module, and a crop growth (CROP) module. The SOM module consists of three pools: fresh, labile and stable. Carbon and nitrogen dynamics in the model are described in terms of carbon turnover, assimilation and dissimilation, with nitrogen linked through distinct C/N ratios. The SOIL module has two soil layers of 15 cm each, and the labile and stable pools are replicated for these two layers. Water, crop and soil management practices and aeration characteristics of these layers affect the C and N dynamics of their respective pools. The CROP module calculates potential and actual biomass, LAI, evapotranspiration, total N demand, actual N uptake and N stress. Actual biomass is first partitioned between above (leaves, stem and storage organs) and below ground (roots and rhizodeposition), and a harvest index (HI) is applied to the aboveground biomass to calculate the yield. Independent data sets of 9 long-term experiments (LTEs) from the IGP of India are used for calibration and validation of the model. After calibration and validation, the model is applied to explore the impact of various crop and soil management practices in rice-based cropping systems in different sites of the IGP. Overall, the model satisfactorily reproduced observed crop yields, SOC dynamics and total soil N dynamics for various cropping systems at different sites. Nitrogen mineralized from soil organic matter contributed 20 to 80% to total N uptake in fertilized and non-fertilized treatments. With a recommended NPK application, a significant decrease in yield was found only in Ludhiana-3 and Pantnagar. Pantnagar had a significant decline in SOC, whereas Ludhiana-3 had a significant increase. An increase in SOM is not always associated with an increase in yield, as the factor(s) improved by an increase in SOM may not be the limiting factor for crop growth. Depletion of many major macro (NPK) and micro (Zn, Fe, Mn, etc.) nutrients essential for plant growth even with a balanced NPK fertilizer application and a maintained SOC can lead to a decline in productivity.

Keywords: Long-term experiment, wheat, soil organic carbon, nitrogen, organic matter dynamics

Introduction

Soil organic matter (SOM) is an absolute condition for sustained agricultural productivity (Reeves, 1997). The role of SOM as a nutrient source for the crop and a physical conditioner for the soil makes it an essential component of the crop production system. Approximately 10 percent of the total (1500 Pg[1]) terrestrial soil organic carbon (SOC[2]) store is found in arable cropping systems (Post, 1990; Eswaran et al., 1993). Organic matter content of a soil depends on its vegetation and the environmental conditions to which it is exposed. Soil organic matter decomposition rates are approximately five times higher in warm, wet tropical and subtropical regions than under temperate conditions (Sanchez and Logan, 1992). Agricultural practices may increase or decrease SOC content, depending on cropping system, cropping intensity, and soil management (Johnson et al., 1995; West and Post, 2002). Higher relative decomposition rates in agro-ecosystems than in natural ecosystems are mainly due to increased disturbance (Carter et al., 1997). Therefore, modifying soil management can potentially result in increased accumulation rates of SOC, thus sequestering CO_2 from the atmosphere (West and Post, 2002).

A land use system based on rice-wheat rotations, common in the IGP, with its annual cycles of wet and dry, puddling and plowing is unique and exerts a specific influence on SOM dynamics. Recent reports have associated yield ‘stagnation’ in some parts of the IGP with a decline in SOM quantity and quality (Dawe et al., 2000; Ladha et al., 2003). Puddling under flooded conditions destroys soil aggregates and disperses clay and SOM particles. Drainage, following harvest of the rice crop, leads to settling of clay particles, which creates a hardpan that makes tillage necessary before sowing wheat. Tillage destroys soil aggregates, increases aeration and exposes SOM, making it more accessible to decomposing micro-organisms. It has been shown (Olk et al., 2000) that continuous flooding leads to build-up of SOM with associated changes in quality and reduced N availability. Similar effects in alternate flooding-draining situations in rice–wheat cropping systems are speculative. Burning of crop residues, common in the Trans- and Upper-Gangetic Plains in combination with mechanical harvesting, contributes to greenhouse gas emissions and substantial loss of soil organic carbon.

In efforts to design a sustainable production system in the IGP to realize the long-term goals of agriculture, the Rice-Wheat Consortium (RWC) for the IGP has introduced

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[1] Pg= 10^{15} g.

[2] Soil organic matter content is often expressed as carbon content; i.e. Soil Organic Carbon (SOC); SOM and SOC are directly proportional: SOC= 0.58 * SOM.

resource conservation technologies (RCTs) for rice and wheat, i.e. practices (zero-tillage, reduced tillage, bed planting, application of manures, etc.) that result in more efficient use of resources such as water, fertilizer and fuel, to sustain or increase land productivity and conserve the environment (Hobbs et al., 2002).

To judge the degree of sustainability of such innovative production techniques for agricultural production systems, quantitative understanding is necessary of the processes determining production and the quality of natural resources (soil, water and air), as influenced by environmental conditions and management practices (Van Keulen, 1995). Since an experimental approach to this problem is problematic as it requires long-term experimentation, which is laborious and time-consuming, a modeling approach to the exploration of the dynamics of sustainability indicators seems promising for evaluation of different management strategies. Therefore, for exploration of the long-term effects of intensive cultivation on soil C and N dynamics, and on crop yields, a summary model, based on sufficient knowledge of the underlying processes is a useful tool, as it can make these long-term effects explicit.

In this paper, we describe and apply a summary model that can be used to investigate the role of soil organic matter in yield formation in rice-based cropping systems in the IGP, as a support tool in identifying possible reasons for declining yield in the region.

Model description

Soil organic carbon and nitrogen (SOM) module

The approach used in the present study is based on the PAPRAN model (Seligman and Van Keulen, 1981) and the long-term model by Van Keulen (1995). Combining the two approaches, in the present model three organic matter pools are distinguished: fresh, labile and stable (Figure 1). Carbon and nitrogen dynamics in the model are described in terms of carbon turnover, assimilation and dissimilation, with nitrogen linked through distinct C/N ratios. Total C turnover in each time interval is the sum of the rates of decomposition of the fresh, labile and stable pools. Total carbon assimilated in microbial biomass, originating from indigenous and freshly added organic matter is assumed to enter the labile SOC pool. The complementary fraction is dissimilated and released as carbon dioxide.

Organic substrates entering the system in the form of roots, rhizodeposition, green manure, straw and/or Farm Yard Manure (FYM) are combined in the fresh organic carbon pool (FOC). This pool is assumed to consist of carbohydrates, cellulose, and

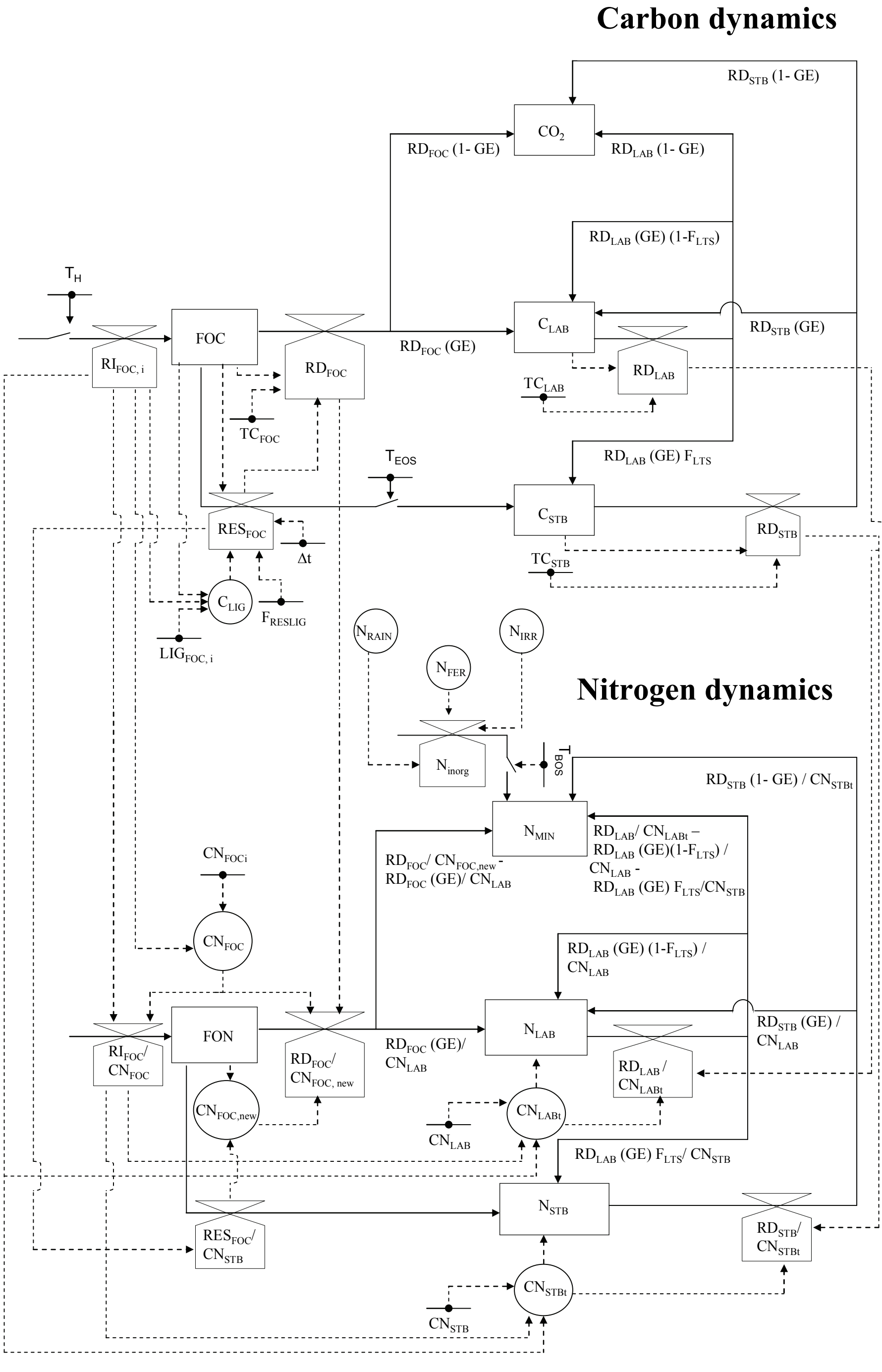

Figure 1. Relational diagram of soil organic matter pools and their dynamics.

T_H – Time of harvest; $RI_{FOC,\ i}$ -rate of fresh organic carbon input as roots, straw, FYM, etc.; FOC- Fresh organic carbon pool; C_{LAB}- Labile C pool; C_{STB}- Stable C pool; FON- Fresh organic N; N_{LAB}- Labile N; N_{STB}- Stable N; C_{LIG}- lignin content of FOC; RD_{FOC}- rate of decomposition of FOC; RES_{FOC}- rate of transfer of FOC to the stable pool; GE- effective growth efficiency i.e. the amount of carbon incorporated into microbial biomass per unit of carbon decomposed; RD_{LAB}- rate of decomposition of labile-C; F_{RESLIG}- fraction of lignin transferred to the stable pool; F_{LTS}- fraction of decomposed carbon transferred from labile to the stable pool; TC_{FOC}- time constant for FOC; TC_{LAB}- time constant for labile pool; TC_{STB}- time constant for stable pool; $CN_{FOC,\ i}$ and $LIG_{FOC,\ i}$ -C/N ratio and lignin content of roots, straw, rhizodeposition, and manures added to the FOC pool; CN_{FOC}- C/N ratio of FOC pool; $CN_{FOC,new}$- C/N ratio of the remaining C in FOC pool after transferring N to the stable pool associated with the lignin; CN_{LAB}- C/N ratio of labile pool; CN_{STB}- C/N ratio of stable pool; CN_{LABt} and CN_{STBt} are C:N ratios of labile and stable pools at time *t*; N_{MIN}- mineral N pool; N_{RAIN}, N_{IRR}, N_{FER}- N contribution through rainfall, irrigation and fertilizer, respectively; Δt is the time step of integration; T_{EOS}– Time at the end of season; T_{BOS}-time at the beginning of season.

lignin with approximate time constants (time needed to reach an equilibrium at a fixed rate of decomposition) of 5, 20 and 105 days, respectively (Seligman and Van Keulen, 1981). The unit of the time constants for decomposition of the various pools in the model is *year*, and the time step (Δt) used in the model is 0.2 y. The proportions of the three biochemical components vary among the fresh organic substrates added to the soil and their lignin content influences the rate of decomposition. Average lignin-C content of the composite fresh organic carbon pool (C_{LIG}; g lignin-C g^{-1} biomass-C) is calculated from the rate ($RI_{FOC,i}$; g biomass-C /Δt) and lignin-C content ($LIG_{FOC,i}$; g lignin-C g^{-1} biomass-C) of the fresh organic inputs as roots, straw, GM, FYM, etc., as follows:

$$C_{LIG} = \frac{\sum_{i=1}^{n} RI_{FOC,i}\left(LIG_{FOC,i}\right)}{\sum_{i=1}^{n} RI_{FOC,i}}$$

The model assumes that within a time step of 0.2 y, most of the fresh organic carbon has vanished and only part of the lignin remains that has a very low rate of decomposition, identical to the stable pool. This is considered as 30% (F_{RESLIG}, 0.3) of the total lignin-C initially present in the FOC and is transferred to the stable pool at the end of a season (Figure 1). The remaining carbon that undergoes decomposition is

$$RD_{FOC} = (FOC - RES_{FOC}\,(\Delta t))/TC_{FOC}$$
$$RES_{FOC} = FOC\,(C_{LIG})\,F_{RESLIG}/\Delta t$$

where TC_{FOC} is the time coefficient of the FOC pool. RES_{FOC} is the rate of transfer of carbon from FOC to the stable pool, realized only at the end of the season.

The actual rate of decomposition of FOC, i.e. RD_{FOC}, results in an exponential decay. Since the time coefficient of the FOC pool, TC_{FOC} (0.03 y) is smaller than the time step (0.2), RD_{FOC} is calculated for the remnant of FOC after transfer of the recalcitrant fraction (RES_{FOC}) to the stable pool (Figure 1).

Part (growth efficiency, GE in kg kg^{-1}) of the carbon from the decomposed material (RD_{FOC}) is incorporated into microbial biomass, and the complementary fraction (RD_{FOC} (1–GE)) is released as CO_2. Growth efficiency reported by Seligman and van Keulen (1981) is 0.5. Since microbes may undergo a number of cycles in a season (0.2 y) when substrates are readily available, the substrate is assumed to pass on average three times through the microbial biomass (turnover). Therefore, in the current model the effective growth efficiency is set to 0.125.

Indigenous organic matter, i.e. that initially present in the soil, is partitioned into two pools: labile and stable. The labile pool comprises carbon originating from the FOC and stable pools after microbial transformation. Microbial biomass is not considered separately, but as part of the labile pool. The time coefficients for the labile and stable pools are 6.7 and 66.7 years, respectively, under optimum soil moisture and temperature conditions (Van Keulen and Seligman, 1987). The labile and stable pools are initialized by allocating total measured SOM between the two in a ratio corresponding to equilibrium, derived from the length of the period the soil has been cultivated. Soil under natural vegetation is characterized by a relatively high labile: stable organic matter ratio. Under cultivation, this ratio decreases. In the EPIC model (Williams, 1995) the labile fraction of organic N is calculated by an equation derived from comparison of organic N levels of soils under natural vegetation with those of adjoining soils under cultivation. Assuming C to be stoichiometrically related to N, the fraction labile (F_{LAB}) in the organic pool is calculated as:

$$F_{LAB} = 0.4\, e^{(-0.0227\, YC)} + 0.1 \qquad (1)$$

Where YC is the length (years) of the period under cultivation.

According to this equation, a soil at the start of cultivation has a labile:stable ratio of 1:1 and the proportion of labile material continuously decreases under cultivation. Initial labile (C_{LABI} in g m^{-2}) and stable (C_{STBI} in g m^{-2}) C are calculated from total initial C ($C_{total,i}$ in g m^{-2}), which is an input to the model.

$$C_{LABI} = C_{total,i}\, F_{LAB}$$
$$C_{STBI} = C_{total,i} - C_{LABI}$$

Decomposition of these two soil organic matter pools is described by first-order kinetics:

$$\left(\frac{dC}{dt}\right)_i = -\, k_i\, C_i$$

where C_i is the amount of organic matter in the i^{th} pool and k_i the relative rate of decomposition of pool *i*.

During decomposition of the labile pool, a fraction (i.e. microbial biomass, GE) is returned to the labile pool and the remainder (1–GE) is released as CO_2. Assuming that microbial biomass consists of both labile and stable components, part of the microbial carbon is transferred to the stable pool (F_{LTS}). Therefore, the net fraction 'returning' to the labile pool is GE ($1–F_{LTS}$) (Figure 1). On decomposition of the stable pool, all carbon from the decomposed material is partitioned between the labile (GE) pool and CO_2.

Summarizing:

Total C turnover = $RD_{FOC} + RD_{LAB} + RD_{STB}$
C assimilated = $(RD_{FOC} + RD_{LAB} + RD_{STB})$ GE
C dissimilated = Total C turnover – C assimilation
Net rate of change of the labile pool = $(RD_{FOC} + RD_{STB})$ GE + RD_{LAB} (GE) $(1–F_{LTS}) – RD_{LAB}$
Net rate of change of the stable pool = $RES_{FOC} + RD_{LAB}$ (GE) $(F_{LTS}) – RD_{STB}$

where RD_{LAB} and RD_{STB} are the rates (g $m^{–2}$ $y^{–1}$) of decomposition of the labile and stable carbon pools, respectively.

In the model, nitrogen dynamics are stoichiometrically related to those of carbon and are calculated as a function of the C/N ratio. Initial total nitrogen ($N_{total,i}$ in g $m^{–2}$) is calculated from the initial C/N ratio ($CN_{total,i}$) of the soil, which is also an input to the model. Assuming organic nitrogen (F_{org}) to be about 0.95–0.99 of total nitrogen, initial labile (N_{LABI}) and stable (N_{STBI}) nitrogen pools (g $m^{–2}$) and their C/N ratios are calculated as:

$N_{total,i} = (C_{total,i} / CN_{total,i})$
$N_{total,i ,org} = N_{total,i} (F_{org})$
$N_{LABI} = N_{total,i, org} (F_{LAB})$
$N_{STBI} = N_{total,i ,org} – N_{LABI}$
$CN_{LABI} = C_{LABI} / N_{LABI}$
$CN_{STBI} = C_{STBI} / N_{STBI}$

where $N_{total,i ,org}$ is total organic soil N.

The labile pool is assumed to consist of microbes and the labile components of dead microbial biomass. Therefore, the C/N ratio of the substrates moving to the labile pool from fresh and stable pools is set to 10. The substrate added to the stable pool, that contains the stable components of the dead microbial biomass, is assumed to have a C/N ratio (CN_{STB}) of 20. However, the initial C/N ratios of the labile and stable pools could be different from the assumed 10 and 20, depending on land use history and quality of the substrates added over the years. The proportions of different species of micro-organisms in the microbial population (C/N ratio: bacteria 5; fungi 10) determine the C/N ratio of the labile pool. These proportions depend on the C/N ratio of the substrates available for decomposition. When substrates are added with a higher C/N ratio, the fungal population dominates the microbial community, and with a lower C/N ratio, this domination is reversed. Similarly, for the stable pool, the C/N ratio of the lignin fraction of FOC, that varies between 10 and 40 (Garnier et al., 2003) influences its C/N ratio. The C/N ratios of the labile (CN_{LABt}) and stable (CN_{STBt}) pools dynamically change under the influence of the rates of addition/removal of C and N to/from these pools over time. The amount of N that is mineralized during their decomposition depends on their current C/N ratio (CN_{LABt} and CN_{STBt}), whereas the N that is added to these pools is calculated from the carbon addition and the fixed C/N ratios of 10 and 20, respectively.

Nitrogen dynamics are described similar to those of C:

$$\text{Total N turnover} = RD_{FOC}/CN_{FOC,\ new} + RD_{LAB}/CN_{LABt} + RD_{STB}/CN_{STBt}$$
$$\text{N assimilation} = (RD_{FOC} + RD_{LAB} + RD_{STB})\ GE\ /CN_{LAB}$$
$$\text{N mineralization} = \text{total N turnover} - \text{N assimilation}$$

where $CN_{FOC,\ new}$ is the C/N ratio of the FOC pool, excluding the C and N from the lignin that is transferred to the stable pool.

In the model, net nitrogen addition to the mineral pool (N_{MIN}) from FOM is that part of the mineralized N that remains after meeting the C/N ratios of the target pools during the carbon transformations:

$$RD_{FOC}/CN_{FOC,new} - (RD_{FOC})\ GE/CN_{LAB}$$

The net rate of change of nitrogen in the labile pool equals:

$$(RD_{FOC} + RD_{LAB} + RD_{STB})\ GE/CN_{LAB} - RD_{LAB}\ (F_{LTS})\ GE/CN_{STB} - RD_{LAB}/CN_{LABt}$$

The net rate of change of nitrogen in the stable pool equals:

$$RES_{FOC}/CN_{STB} + RD_{LAB}\ (GE)\ (F_{LTS})/CN_{STB} - RD_{STB}/CN_{STBt}$$

where CN_{LABt} and CN_{STBt} are the C/N ratios of the labile and stable pools, respectively at time *t*.

Factors influencing SOM decomposition

Actual relative rates of decomposition of the labile and stable pools depend on environmental conditions, i.e. temperature, moisture, texture, pH and management such as tillage and puddling. Effects of these factors are interactive, for example, sensitivity to temperature depends on moisture conditions and vice versa (Bunnell et al., 1977; Goncalves and Carlyle, 1994; Grant and Rochette, 1994; Sierra, 1997; Leiros et al., 1999; Qi and Xu, 2001). The effect of moisture and temperature is also influenced by soil texture and management. Under optimum temperature and below-optimum moisture conditions, the relative decomposition rate (k) increases with increasing moisture content, which is the rate-determining factor. However, under sub-optimal temperature and moisture conditions, k is not only limited by moisture but also by temperature. Therefore, the effect of these two factors on k is expressed in the model in a multiplicative way (Bunnell et al., 1977; Goncalves and Carlyle, 1994).

Since pH may limit microbial processes similarly to temperature or moisture, its effect is included in the model through a correction factor that modifies k in a multiplicative way. Soil texture influences k through the protective effect of clay on the substrate. Soil tillage also affects k through its influence on substrate availability. Differences in substrate availability as a result of protection by clay and tillage are expressed in the model as rate-modifying factors, varying from 0-1. Thus, the final equation for decomposition of the soil organic matter pools becomes:

$$\left(\frac{dC}{dt}\right)_i = -\,k_i\,C_i\,T_{fac}\,M_{fac}\,PH_{fac}\,X_{fac}\,TL_{fac}$$

where T_{fac}, M_{fac}, PH_{fac}, X_{fac} and TL_{fac} express the effect of temperature, moisture content, pH, texture, and tillage, respectively.

Environmental factors

Temperature

Most existing SOM models use Van ’t Hoff (Q_{10}) or Arrhenius equations to describe the effect of temperature on organic matter decomposition. Q_{10} is a constant that represents the increase in relative decomposition rate with a 10 °C increase in temperature. Generally, the response of decomposition is steeper in the low temperature range (Ross and Cairns, 1978; Addiscott, 1983; Ellert and Bettany, 1992) than in the high temperature range, so that the value of Q_{10} decreases at higher temperatures (Kononova, 1975; Schleser, 1982; Lloyd and Taylor, 1994; Kirschbaum, 1995; Rodrigo et al., 1997). Kirschbaum (1995) reported a decrease in Q_{10} from 8 at 0 °C to 2.5 at 20 °C. To describe the effect of temperature on k, the function used in the DNDC model (Li et al., 1994; Shibu et al., 2006) is used in the present study:

$$T_{fac} = ((60–T)/25.78)^{3.503}\ e^{(3.503\ (T– 34.22)/25.78)}$$

where T is mean seasonal temperature (°C).

Moisture and aeration

The effect of soil moisture on decomposition rate can be expressed in terms of soil water potential, relative water content (the ratio of (actual water content minus water content at lower limit) and (water content at upper limit minus that at lower limit)) or water-filled pore space (Rodrigo et al., 1997). In rice-based cropping systems, in which an upland crop such as wheat follows a flooded rice crop, aerobic and anaerobic soil conditions alternate, each time changing soil bio-physicochemical properties. The water-filled pore space (WFPS), the ratio of actual water content to water content at saturation, is the best indicator for (micro)biological activity in such alternating aerobic/anaerobic soil conditions (Linn and Doran, 1984). WFPS influences soil microbiological processes through its effect on moisture and aeration. As WFPS increases, gradually anaerobic conditions develop. The active microbial population changes from aerobic to facultative anaerobic and oxygen for microbial activity is supplied by alternative sources ($NO_3^–$, Mn^{4+}, $SO_4^{2–}$, etc.) instead of atmospheric oxygen diffusing into the soil. This reduces the rate of organic transformation processes and the end products change from $NO_3^–$ and CO_2 to N_2O and/or N_2 and methane.

The rate-modifying factor for moisture is calculated as (Li et al., 1994):

If WFPS > 0.05
M_{fac} = 1.01– 0.21 WFPS,
else: M_{fac} = 0.0

Aeration mainly affects the type of reaction and the end product. Under continuous flooding, as for rice, the redox potential in soil is low enough (–150 mV) for methane production (Wang et al., 1993). Methane production is highly correlated with rice biomass and temperature and is soil texture- and crop variety-specific. To calculate CH_4 production and emission, we used a semi-empirical approach (Huang et al., 1998;

2004). Seasonal methane production (SMP) is the sum of CH_4 produced (g m^{-2}) in association with rice plants:

$$SMP_{crop} = 4.86 \times 10^{-5}\ B_{mean}\ T_{fac}\ V_{fac}\ S_{fac}\ Eh_{fac}\ t_{eff}$$

and that produced during anaerobic oxidation of added organic residues:

$$SMP_{res} = 0.27\ RD_{FOC}$$

where the constant 4.86×10^{-5} is the rate of methane production per unit biomass (g CH_4 g^{-1} biomass d^{-1}); B_{mean} is mean seasonal biomass production (55% of the biomass at harvest, g m^{-2}), T_{fac}, V_{fac}, S_{fac} and Eh_{fac} are dimensionless correction factors for temperature, variety, soil texture (sand %) and redox potential, respectively; t_{eff} is length of the period contributing to methane production in the cropping season (d); RD_{FOC} is the fresh organic carbon decomposed (g m^{-2}); and 0.27 is the conversion factor on a mole weight basis of $C_6H_{12}O_6$ to CH_4 (Huang et al., 2004).

Methane production is assumed to start after 3 weeks of continuous flooding, while 75 percent is produced in the last 5 weeks of crop growth (Huang et al., 1997a; b). However, the fraction emitted declines, as aerenchyma cells become well developed towards the end of crop growth and oxidation is enhanced. Therefore, an emission factor (EF, 0.35) is used to calculate seasonal emission (SME) from total methane production:

$$SME = (SMP_{crop} + SMP_{res})\ EF$$

Soil texture/structure

SOC-content is positively correlated to clay content (Ladd et al., 1985; Oades, 1988; Amato and Ladd, 1992). Studies have shown that the higher SOC-content associated with an increase in clay content is related to the specific surface area of the clay minerals (Saggar et al., 1996; Ransom et al., 1998; Bock and Mayer, 2000), water holding capacity and volumetric water content (Schjønning et al., 1999; Thomsen et al., 1999). Soil aggregation (Amelung and Zech, 1996) and pore size distribution (Kilbertus, 1980) also influence stabilization of organic carbon through their effect on the physical barrier between substrate and decomposing organisms. This so-called ‘protection’ does not imply permanent and complete removal of organic carbon from the decomposing pool, but a reduction in the relative rate of decomposition compared to organic carbon in a non-protected situation (Krull et al., 2003). However, the protective capacity (the total amount of SOC that can be protected) of a soil is finite (Hassink, 1996; Hassink et al., 1997; Krull et al., 2003) and the proportion of added organic carbon that can be protected depends on the extent of saturation of the protective capacity of the soil.

The effect of soil texture on organic matter decomposition is included in the model through a rate-modifying factor (X_{fac}), which is accounting for the (temporary) reduction in substrate availability to decomposition. The rate modifying factor (X_{fac}) is defined as a function of silt and clay content of the soil (Ladd et al., 1981; Parton et al., 1987; Verberne et al., 1990; Hassink, 1995; Van Keulen, 1995):

$$X_{fac} = 1 - 0.75\ (\text{silt fraction} + \text{clay fraction})$$

pH

Studies, mainly in acidic soils, have shown that microbial biomass and CO_2 release increase with increasing soil pH (Adams and Adams, 1983; Carter, 1986; Amato and Ladd, 1992; Motavalli et al., 1995). The effect of pH on the relative rate of decomposition is calculated in the model according to the approach used in ANIMO (Groenendijk and Kroes, 1999).

$$pH_{fac} = \frac{1}{1 + \exp^{-2.5(pH-5)}}$$

Soil salinity and sodicity

Reports on the effects of salinity and sodicity on SOM decomposition (el-Shakweer et al., 1977; Nelson et al., 1996; Wong et al., 2004) are conflicting. These show either an increasing microbial biomass and CO_2 evolution by soil respiration with increasing sodicity and salinity or a decrease with increasing salinity. More research is needed for exact quantification of the relations. It is speculated that high EC (Electrical Conductivity) and ESP (Exchangeable Sodium Percentage) or SAR (Sodium Adsorption Ratio) cause dispersion and slaking of aggregates and enhance exposure of soil organic matter (Laura, 1973; Jandle and Sollins, 1997; Wong et al., 2004). Since no reliable data were found in literature to describe the relation between relative rate of decomposition and ESP or SAR, we did not include it in the model.

Management factors

Puddling and tillage

Management practices, such as tillage and residue management mainly influence soil physical properties. Tillage breaks up the soil aggregates, increases aeration and enhances microbial activity, resulting in increased decomposition of SOC. The effect of no-tillage on relative decomposition is included in the model through a 10% reduction in relative decomposition rate on a seasonal basis. Puddling has a similar effect on SOC as conventional tillage (CT), and therefore, the relative rate of decomposition of SOC is modified as under CT. However, flooding following puddling will reduce decomposition through the effect of anaerobiosis. It is assumed that the effect of puddling or tillage persists over a crop season.

Residue management

The major residue management options include residue burning, removal and incorporation. The model assumes that when residues are removed or burned after harvest, no carbon from residues is returned to the soil, whereas incorporation implies return of all C in the stubbles to the soil. However, the proportion of straw incorporated depends on the method of harvesting. Under manual harvesting about 10% is returned, while it is 30% under mechanical harvesting.

SOIL module

In the SOIL module, two soil layers of 15 cm each are distinguished. Even though roots may extend beyond 1 m depth, the upper 30 cm is important agronomically (puddling and tillage influence this layer) and for soil carbon and nitrogen dynamics. Water content and temperature are the two major environmental conditions influencing the dynamics of carbon and nitrogen in soil. These conditions depend on ambient conditions and soil physical properties, such as bulk density, water-holding capacity (WHC) and soil hydraulic conductivity. Temperature in the model is set to the seasonal mean average temperature of the site, since variation within a season is relatively small (Timsina and Connor, 2001; White and Rodriguez-Aguilar, 2001). Soil water content is assumed to be either at field capacity or at saturation depending on cropping period. For rice, the field is mostly puddled, and flooded or saturated and in the model saturated field conditions are assumed. On the other hand, for an upland crop such as wheat, which is mostly irrigated, soil water content is assumed to be at field capacity.

Soil inorganic nitrogen

Contribution of NO_3^--N from rainfall and irrigation

The nitrogen contribution (kg ha^{-1}) from rainfall is calculated according to Parton et al. (1987):

$$N_{PPT} = 0.21 + 0.0028\ PPT$$

where PPT is total annual rainfall in cm and 0.21 represents the dry deposition.

The nitrogen contribution from irrigation depends on amount and nitrogen concentration of irrigation water. Since the amount of irrigation water applied varies for different sites, an average irrigation dose and nitrogen concentration (mg l^{-1}) are used.

Nitrogen deposition from rainfall and irrigation and nitrogen mineralized from organic residues or applied as chemical fertilizer directly enters the mineral pool (Figure 1). Part of the nitrogen from the mineral pool is lost from the system (volatilization, leaching and denitrification). These losses are not simulated explicitly, but we use a crop-specific nitrogen recovery fraction (NRF) to estimate crop available N in dependence of crop and soil management. Nitrogen mineralized from indigenous organic matter is assumed to be directly available to the crop (with a NRF equal to 1), and is taken up before mineral nitrogen from fertilizer and residues.

Biological N-fixation

N-fixation by free living blue green algae (BGA) is a potential source of N, especially in rice, since anaerobic conditions promote the growth of BGA. Information about N-fixation in cereals is scanty and conflicting. Cassman et al. (1998) report values in the order of 30-50 kg ha^{-1} in rice. However, Giller and Merckx (2003) report non-symbiotic N-fixation in natural systems to be less than 5 kg ha^{-1} y^{-1}. Therefore, for the time being we did not consider N-fixation in the model.

CROP module

Crop growth is a function of radiation and temperature, and water and nutrient availability. Temperature influences crop phenological development rate, and in the model, development stage is defined as a function of the heat sum, i.e. the cumulative effective (above a threshold temperature) temperature. Since biomass production depends on water and nutrient availability until flowering, the model distinguishes two stages of crop development: pre-flowering and post-flowering, characterized by the heat sums from emergence to flowering and flowering to maturity, respectively.

Under ample supply of water and nutrients and in the absence of yield reducing factors, yield (potential) is determined by radiation interception (De Wit and Penning de Vries, 1982; Penning de Vries et al., 1989). The model calculates the potential yield until flowering and reduces the potential yield to *water-limited* and/or *N-limited* yield due to water and/or nitrogen deficiency. The crop module uses light use efficiency (LUE) to calculate biomass formation (Monteith, 1977; 1990). Potential biomass produced (B_p, g m^{-2}) is calculated as:

$$B_p = Q_{cum}\, LUE$$

where, Q_{cum} is cumulative (for an average crop duration) intercepted photosynthetically active radiation (MJ m^{-2} surface area) and LUE is light use efficiency (g MJ^{-1}).

Cumulative PAR intercepted by the canopy is calculated using Lambert-Beer's law:

$$Q_{cum} = 0.5\, Q_{0,cum}\, [1 - \exp^{(-k\, LAI)}]\, ICF$$

where, $Q_{0,cum}$ is cumulative global radiation (MJ m^{-2}), and k the light extinction coefficient for PAR, LAI represents maximum LAI at flowering, and ICF is the interception correction factor, accounting for the effectively intercepted light over the whole growing period, including the initial exponential phase, before maximum LAI (6.0, under potential conditions) is attained. The value of ICF is calculated based on the results of a crop model (LINTUL3, Chapter 4) with a time resolution of one day.

Water stress affects biomass production through a transpiration reduction factor, defined as the ratio of actual to (seasonal) potential evapotranspiration. Potential evapotranspiration is calculated according to the Makkink (1957) approach, considering only the radiation-driven part of the Penman equation, the most important term in the evapotranspiration equation (Priestley and Taylor, 1972). It uses short wave radiation, assuming a constant ratio (0.5) between net and short wave radiation.

$$ET_p = C\, \frac{1}{\lambda} \frac{R_s S}{S + \gamma}$$

Where ET_p is potential evapotranspiration (mm $season^{-1}$), C is Makkink's constant (0.63), λ the latent heat of vaporization (2.4 MJ kg^{-1}), R_s total short wave radiation (MJ m^{-2} $season^{-1}$), S the slope of the saturated vapor pressure curve (kPa $°C^{-1}$), and γ the psychrometer constant (kPa $°C^{-1}$).

Actual evapotranspiration (ET_a, mm $season^{-1}$) depends on water availability in the soil and potential demand. Total soil water is the net balance of rainfall, irrigation, transpiration, evaporation, drainage, and runoff. A transpiration reduction factor (TRF) linearly reduces potential biomass production to water limited biomass production as:

$$B_{wl} = B_p \, TRF$$

$$TRF = (ET_a/ET_p)$$

Sub-optimal nitrogen availability in the soil leads to sub-optimal crop nitrogen concentrations, which is defined as N stress, where crop growth is negatively affected and yield is reduced, when N concentration drops below the *critical* value, defined as half the maximum N concentration (Jamieson and Semenov, 2000). Nitrogen supply (g N m^{-2}) is the sum of indigenous N supply of the soil (associated with SOM decomposition) and nitrogen supply from fertilizer, rainfall and irrigation. Nitrogen stress is expressed in the model through a growth reduction factor, the nitrogen nutrition index (NNI), calculated up to flowering as the ratio of available N in the soil (g m^{-2}) and critical plant N demand (g m^{-2}). Available N includes the supply from fertilizers and manures after possible losses and the nitrogen mineralized from soil organic matter, which is directly available to the plant for uptake. The nitrogen nutrition index affects maximum LAI and reduces total biomass production through its effect on PAR interception.

$$Q_{cum} = 0.5 \, Q_{0,cum} \, [1 - \exp^{(-k\,(LAI*NNI))}] \, ICF$$

Total biomass is partitioned among the various organs: Fifteen percent is partitioned belowground, i.e. roots (5%) and rhizodeposition (10%), and the remainder is partitioned between straw and storage organs based on the harvest index (HI) (see Appendix).

Model parameterization, sensitivity analysis, calibration and validation

Parameterization

Model parameters characterizing soil organic matter dynamics and crop growth were derived from literature, and when not available, based on understanding of the system and expert knowledge, using the available datasets. A complete list of parameters used in the model is given in the Appendix.

Partitioning of SOC into a labile and a stable pool meets the minimum requirement to describe the heterogeneity of SOC that consists of a mixture of components ranging from highly decomposable to very recalcitrant. Therefore, initialization of the labile and stable pools in the model is associated with uncertainty. In the present study, the sites Pantnagar and Barrackpore were under natural vegetation before the start of the experiments and therefore, a labile:stable ratio of 1:1 for these sites was assumed. Samastipur has a longer cropping history, since this is the site where the first university in India was established in 1905. Therefore, we assumed a ratio of 1:4 according to Equation 1. Since we did not know the history of the other sites, we assumed that they have been under cultivation for at least 30 years before the start of the experiment and a labile:stable ratio of 1: 2.3 was used.

Relative rate parameters for decomposition associated with these pools are adopted from Seligman and van Keulen (1981) and van Keulen (1995) (Appendix). Carbon/nitrogen ratios of labile (20) and stable (10) pools defined by Van Keulen (1995) were modified to 10 and 20, respectively, since the labile fraction is assumed to comprise mainly the microbial biomass and its derivatives. The carbon/nitrogen ratio of the FOM pool depends on the C:N ratio of the different substrates added to this pool. Carbon concentration in plant biomass varies (35-45%), depending on species and plant part. In the model, the average carbon concentration in plant biomass is set to 40%. Variations in N concentration among different plant parts are large, which in the model is reflected in their C:N ratios (see Appendix).

Crop parameters for different crops were derived from the detailed model for rice (Chapter 4), assuming similar basic crop physiological functioning for various crops. Biomass production is derived from light intercepted by the canopy, using the light use efficiency (LUE in g per MJ) approach (Monteith, 1977; Gallagher and Biscoe, 1978; Monteith, 1990), assuming species specific LUE-values (see Appendix). For rice and wheat a LUE value of 3.0 is used (Kiniry et al., 1989; Sinclair and Muchow, 1999; Choudhury, 2001; Kiniry et al., 2001). For cowpea, reported LUE ranges from 1.6 to 2.1 (Muchow, 1985; Muchow et al., 1993) for aboveground biomass, and when calculated including roots yielded a value of 2.2. For jute, no experimental information on LUE was found. In this case the value was obtained through calibration, using datasets from Biswas et al. (2006) (results not reported here), which yielded a value of 2.8.

Maximum N concentration (calculated as weighted average of leaves, stem, storage organs and roots), corresponding to anthesis is used for calculating total crop N demand, because plants usually accumulate 80-90% of their final N content before anthesis (Cregan and Vanberkum, 1984). In cereals, this nitrogen is translocated to the storage organs after anthesis. For rice, a maximum concentration of 0.03 g g^{-1} is used (Bouman and van Laar, 2006) and for wheat 0.04 (Bameix et al., 1992). Maximum N concentration for cowpea is obtained from an Organic Resources Database (Anonymous, 1997). For jute the value is found by calibration (0.03 g g^{-1}). The critical N concentration, referring to aboveground biomass, is reported as 50% of the maximum N concentration (Jamieson et al., 1998). For total biomass, including roots, the critical N concentration is set to 40% of the maximum. The recovery fraction of N from mineral fertilizers and that mineralized from residues and organic manures is set to 50% for all crops, except for rice (30%), which is cultivated under flooded conditions.

Sensitivity analysis

Sensitivity of SOC dynamics, total nitrogen (organic + mineral) and N supply and crop yield to the major environmental and soil factors (temperature, pH, and silt and clay content) is analyzed under situations of no-fertilizer (Figure 2) for a period of 100 years. The results show an increase in SOC, total nitrogen, nitrogen supply from SOM and crop yield with a 3 °C decrease in temperature from 29 and 23 °C for rice and wheat, respectively. The effect is strongest for nitrogen supply (+21%), whereas the corresponding changes in SOC, total soil nitrogen and crop yield are 10, 10 and 11%, respectively. A similar increase in temperature results in a 17% decrease in SOC and total soil N, whereas the corresponding decreases in N supply and yield are 38 and 19%.

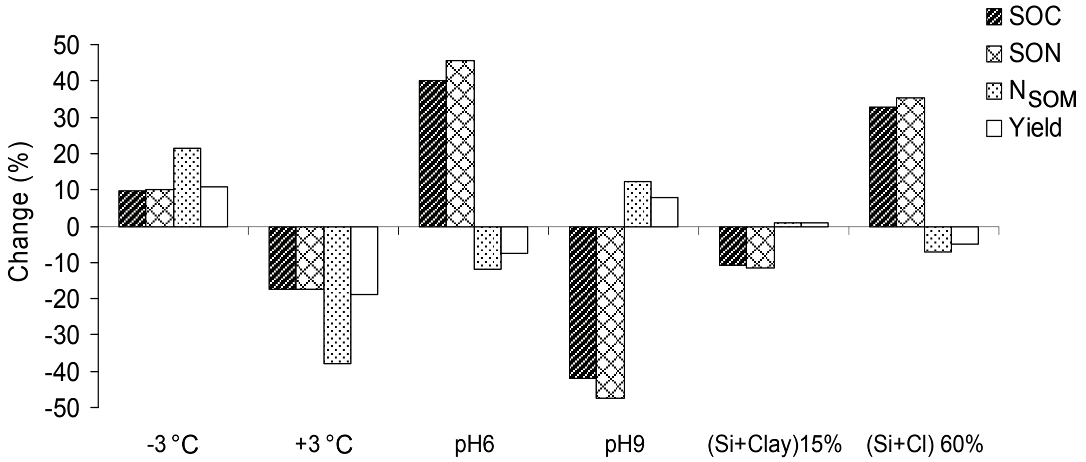

Figure 2. Cumulative changes after simulating for 100 years in soil organic carbon (SOC), soil organic nitrogen (SON), N supply from soil organic matter (N_{SOM}) and crop yield resulting from variations from ambient environmental and soil conditions (29 and 23 °C during summer and winter, respectively; pH 7.5; (silt + clay) 30%) under no-fertilizer application.

A decrease in pH from 7.5 to 6, results in 40% increase in SOC and 45% in total soil N and a decrease in N supply and yield by 12 and 8%, respectively. Lowering soil pH reduces microbial activity and results in lower mineralization and N supply, which eventually results in lower yields. On the other hand, an increase in pH (from 7.5 to 9) results in lower SOC and total N due to higher mineralization, and an associated increase in nitrogen supply and yield.

Silt and clay content of the soil affect the dynamics of SOM indirectly through its effect on moisture holding capacity and directly through organic matter protection. The effect on moisture is implemented by changing the water contents at field capacity (FC) and saturation (SAT). Water content at FC is changed from 0.2 to 0.1 and 0.3 on changing the clay + silt content from 30 to 15 and 60%, respectively. Corresponding changes in water content at SAT are from 0.4 to 0.3 and 0.6. A lower silt and clay content results in a decrease in SOC and total N by 11% and an increase in N supply and yield by 1%, whereas a higher content has a larger impact on SOC (33%) and total N retention (35%), but results in reduced N supply (7%) and crop yield (5%).

Calibration

Methodology

For calibration of the model, datasets Ludhiana-1 and Nadia are used. Site characteristics and experimental details for these locations are given in Table 1, Table 2 and Figure 3. Table 3 gives the average amounts of water used for irrigation in different regions of the IGP (Tripathi, 1996). Irrigation requirements depend on crop, rainfall and soil type.

Variety-specific heat sums for flowering and maturity were calculated from daily temperatures and the number of days to flowering and maturity at each location using actual weather data. Heat sums were calculated as cumulative effective temperatures, i.e. above a base temperature, the threshold below which phenological development ceases. Base temperatures are species- and even variety-specific (van Keulen and Wolf, 1986), varying for rice from 0-10, and for wheat from 0-5 °C. The model uses a base temperature of 8 °C for rice, 0 °C for wheat, for cowpea a value of 10 °C, similar to that reported for soybean (van Keulen and Wolf, 1986) and for jute a value of 8 °C, typical for a tropical crop (Appendix).

Results of calibration

Model calibration for Ludhiana-1 shows an increasing trend in SOC, similar to that observed in Treatment-1 (WS+GM+52 kg N ha^{-1}) and Treatment–2 (150 kg N ha^{-1}),

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

Sites	ACZ	Texture class	Soil type	Clay %	Silt %	pH	BD kg m^{-3}	SOC g kg^{-1}	Total-N g kg^{-1}	Reference
Ludhiana-1	TGP	Ls	Typic Ustipsamment	12.6	9	7.6	1550	3.6	0.45	Yadvinder et al., 2004
Ludhiana-2	TGP	Ls	Typic Ustipsamment	10.9	10	7.2	1550	3.5		Yadvinder et al., 2004b
Ludhiana-3	TGP	Ls	Typic Ustochrept	12.0	9	8.2	1550	3.8	0.67	Bhandari et al., 2002
Karnal	TGP	Sl	Aquic Natrustalfs	15.0	9	8.7	1550	4.0	0.50	Yaduvanshi, 2001
Palampur	TGP		Typic Hapludalf	30.0	54	5.6	1400	8.8	1.35	Sharma et al., 2003
Pantnagar	UGP	Scl	Aquic Hapludoll	20.0	40	7.3	1320	14.8	1.30	Ram, 1998; 2000
Samastipur	MGP	Sl		17.0	9	8.5	1500	5.1		Prasad and Sinha, 2000
Barrackpore	LGP	Sl	Eutrochrept	18.0	9	7.1	1300	7.1	0.86	Saha et al., 1998; 2000; Mandal et al., 1984
Nadia	LGP	Sl		16.5	34.5	7.5	1300	9.4	0.54	Samui et al., 1998; Kundu and Samui (2000)

ACZ: Agro-climatic zone; BD: Bulk density; SOC: Soil organic carbon; TGP: Trans-Gangetic Plain; UGP: Upper-Gangetic Plain; MGP: Middle-Gangetic Plain; LGP: Lower-Gangetic Plain ; Ls : Loamy sand ; Sl : Sandy loam ; Scl : Silty clay loam.

Table 2. Cropping systems (CS) and treatments for the various sites used in the study.

Site	CS[1]	Duration	Tr.No	Treatments[2]			100% NPK fertilizer rate (kg ha^{-1})		
Calibration				Rice	Wheat	3^{rd} crop	Rice	Wheat	3rd crop
Ludhiana-1	R-W	1988-2000	I.	WS+ GM+ N-52 kg ha^{-1}	100% NPK	-	150-0-0	90-26-50	-
			II.	N- 150 kg ha^{-1}	100% NPK	-			
			III.	No-NPK+ no-FYM	100% NPK	-			
Nadia	R-W	1986-1995	I.	50% NPK + 7.5 Mg ha^{-1} FYM	100% NPK	-	100-60-40	100-60-40	-
			II.	100% NPK	100% NPK	-			
			III.	No-NPK+ No-FYM	No-NPK+ No-FYM	-			
Validation									
Ludhiana-2	R-W	1993-2000	I.	100% NPK	RI-120N	-	120-26-25	120-26-25	-
			II.	100% NPK	RR-120N				
			III.	100% NPK	RR-0N	-			
Ludhiana-3	R-W	1983-1997	I.	50% NPK + 6 Mg ha^{-1} FYM	100%NPK	-	120-26-25	120-26-25	-
			II.	100% NPK	100%NPK	-			
			III.	No-NPK+ no-FYM	No-NPK+ no-FYM	-			
Palampur	R-W	1988-1999	I.	10.8 Mg ha^{-1} GM+ 100% NPK	100% NPK		90-18-33	120-26-25	-
			II.	3.6 Mg ha^{-1}+ 100% NPK	100% NPK				
			III.	No GM+ 100% NPK	No-NPK+ No-FYM				
Karnal	R-W	1994-1999	I.	100% NPK+ 10 Mg ha^{-1} FYM	100% NPK	-	120-26-42	120-26-42	-
			II.	100% NPK	100% NPK	-			
			III.	No-NPK+ no-FYM	No-NPK+ no-FYM	-			
Samastipur	R-W	1988-1995	I.	100% NPK+ 10 Mg ha^{-1} FYM	100% NPK	-	100-60-40	100-60-40	-
			II.	100% NPK	100% NPK	-			
			III.	No-NPK+ No-FYM	No-NPK+ No-FYM	-			
Pantnagar	R-W-C	1971-2000	I.	100% NPK+ 15 Mg ha^{-1} FYM	100% NPK	No-NPK	120-26-35	120-26-35	-
			II.	100% NPK	100% NPK	No-NPK			
			III.	No-NPK+ no-FYM	No-NPK+ no-FYM	No-NPK			
Barrackpore	R-W-J	1971-1995	I.	100% NPK	100% NPK	100% NPK+ 10 Mg ha^{-1} FYM	120-26-50	120-26-50	60-13-50
			II.	100% NPK	100% NPK	100% NPK			
			III.	No-NPK+ No-FYM	No-NPK+ No-FYM	No-NPK+ No-FYM			

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[1] R-W: Rice-Wheat; R-W-C: Rice-Wheat-Cowpea; R-W-J: Rice-Wheat-Jute.

[2] RR-0N: Rice residue Removed with no fertilizer-N; RR-120N: Rice residue Removed with 120 kg N ha^{-1} ; RI- Rice residue Incorporated with 120 kg N ha^{-1}; GM – Green Manure; FYM – Farmyard Manure; WS: Wheat Straw.

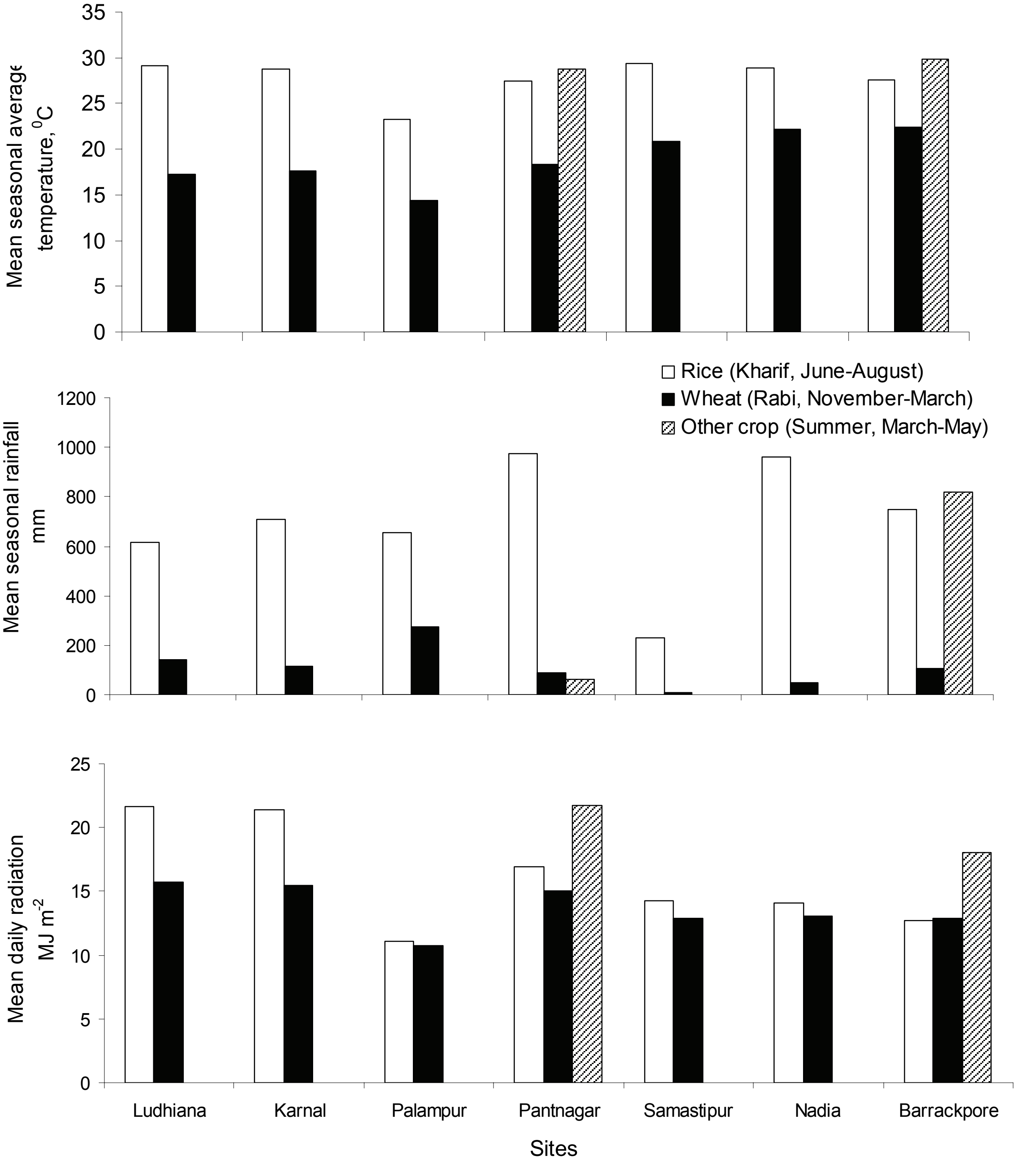


Figure 3. Seasonal mean average temperature, rainfall and radiation in different seasons of the various sites (calculated for the different time periods considered for the simulation, see Table 2).

Table 3. Average values for irrigation water input and N concentration in the irrigation water used in the model for various locations in the IGP under rice-based cropping systems.

	Rice[†] (mm)	Wheat (mm)	NO_3^- –N (mg l^{-1})	N input (kg ha^{-1})		
				Rice	Wheat	Jute
Ludhiana	1900	400	4.0	76.0	16.0	-
Nadia	1200	250	1.0*	12	2.5	-
Karnal	2200	400	4.0*	88.0	16.0	-
Palampur	600	150	1.0*	6.0	1.5	-
Samastipur	810	200	1.0*	8.1	2.0	-
Pantnagar	1210	300	1.0*	12	3.0	-
Barrackpore	1200	250	1.0*	12	2.5	6.0

†Continuous flooding

*no exact data available

Sources: Chaudhary, 1997; Yadvinder et al., 2004a; Sharma et al., 2003; Gupta et al., 2002.

whereas it is constant in Treatment-3 (control), compared to a slight increase in the observations (Figure 4). Simulated crop yields also follow the observed trends. Model-calculated average rice yield (Table 4) was slightly higher in Treatment-2 (6.7 Mg ha^{-1}) than in Treatment-1 (6.1 Mg ha^{-1}), associated with a higher average N uptake (117 vs. 103 kg ha^{-1}), whereas observed yields were similar (5.7-5.8 Mg ha^{-1}). In the control, the average yields observed (3.8 Mg ha^{-1}) and simulated (3.6 Mg ha^{-1}) are similar. The calculated average contribution from organic sources (soil organic matter, residues and added manures) constitutes 50% of total N uptake in Treatments-1 and 3, whereas it is 30% in Treatment-2 with the recommended N fertilizer dose. Out of this 50%, 30-40 % is from SOM and the remaining originates from fresh residues. Average observed wheat yields were similar in all treatments (4.4 Mg ha^{-1}), suggesting absence of residual effects. The model calculated lower yields for Treatments-2 and 3 compared to Treatment-1, associated with lower N uptake values due to differences in N supply from SOM (Table 4).

For Nadia, the model satisfactorily reproduced observed SOC and total N in all treatments (Figure 5). Simulated rice and wheat yields match reasonably well with observed values, albeit wheat yields are overestimated in Treatment-1 (50% NPK +FYM) and Treatment-2 (100% NPK) (Table 4). In rice, SOM supplies 37% of total N uptake in Treatment-1 and Treatment-2 and 76% in the control. In wheat, N uptake in the control is 19 kg ha^{-1}, associated with a calculated yield of 0.6 Mg ha^{-1}, slightly

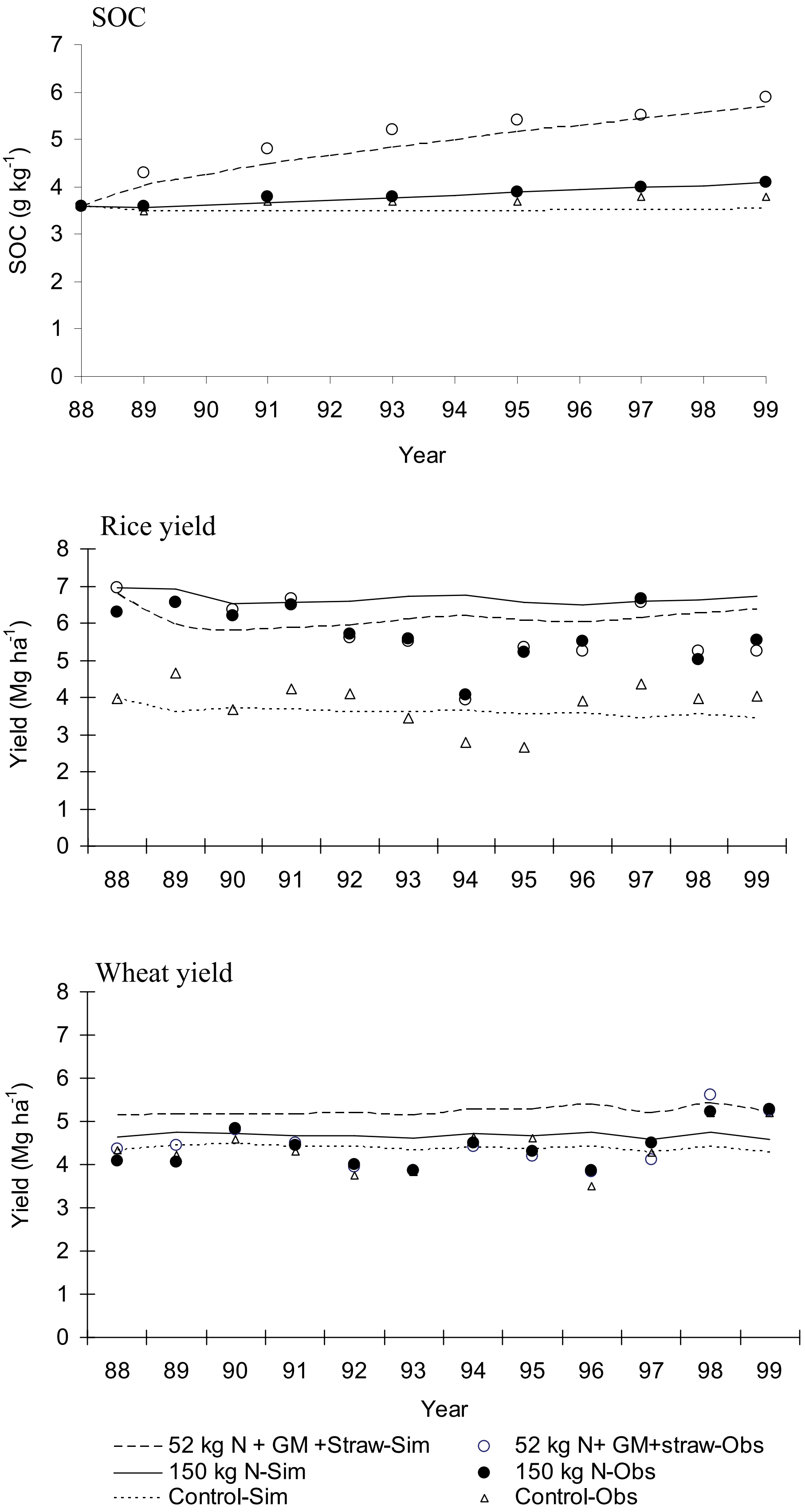


Figure 4. Calibration results for Ludhiana-1 under different treatments.

Table 4. Average crop yields and N uptake from different sources during the cropping periods in different treatments for various sites of the IGP.

	Rice					Wheat					Third crop* (kg ha^{-1})				
	Obs.Y†	Sim.Y	N_{Inorg}**	N_{SOM}††	N_{uptake}	Obs.Y†	Sim.Y	N_{Inorg}**	N_{SOM}††	N_{uptake}	Obs.Y†	Sim.Y	N_{Inorg}**	N_{SOM}††	N_{uptake}
	---- (Mg ha^{-1}) ---		----------(kg ha^{-1}) -----------			---- (Mg ha^{-1}) ---		------------(kg ha^{-1}) --------			---- (Mg ha^{-1}) ---		------------(kg ha^{-1}) ---------		
Treatment-1															
Ludhiana-1	5.8	6.1	49 (47)	32 (31)	103	4.4	5.2	54 (48)	44 (39)	113					
Nadia	3.3	4.0	19 (29)	25 (37)	66	2.5	4.0	52 (54)	37 (38)	97					
Ludhiana-3	5.6	6.4	50 (46)	38 (35)	109	4.7	5.8	86 (65)	31 (24)	133					
Palampur	4.5	4.7	34 (36)	19 (20)	96	3.0	4.9	61 (51)	48 (40)	120					
Ludhiana-2	6.3	6.2	71 (67)	27 (26)	106	5.2	5.0	66 (63)	25 (24)	105					
Karnal	6.4	8.0	85 (55)	38 (25)	153	5.2	6.1	84 (55)	51 (33)	153					
Samastipur	3.4	5.1	39 (39)	34 (34)	100	3.4	4.3	55 (49)	49 (44)	112					
Pantnagar	6.5	6.4	48 (35)	43 (32)	135	4.5	5.4	63 (48)	60 (45)	132	2.7	4.5	3 (4)	37 (53)	70
Barrackpore	4.1	4.7	44 (42)	53 (50)	106	2.5	4.0	64 (63)	29 (28)	103	2.0	2.5	38 (30)	31 (25)	125
Treatment-2															
Ludhiana-1	5.7	6.7	82 (70)	28 (24)	117	4.4	4.7	54 (57)	25 (26)	95					
Nadia	3.5	3.7	33 (54)	23 (37)	61	2.4	3.6	52 (66)	20 (25)	80					
Ludhiana-3	6.2	6.7	70 (62)	35 (31)	114	4.5	5.4	74 (63)	28 (24)	117					
Palampur	4.1	4.1	34 (48)	18 (26)	71	2.7	4.4	61 (62)	29 (29)	99					
Ludhiana-2	6.2	6.2	71 (68)	27 (26)	105	5.0	5.0	67 (63)	24 (23)	106					
Karnal	5.5	7.3	85 (65)	37 (29)	129	5.0	5.7	84 (64)	30 (23)	131					
Samastipur	2.9	4.3	39 (52)	30 (40)	74	3.2	3.8	55 (63)	26 (30)	87					
Pantnagar	5.6	5.1	48 (55)	34 (40)	86	3.8	4.7	63 (62)	31 (30)	101	2.6	3.9	3 (5)	28 (48)	58
Barrackpore	3.9	4.3	45 (54)	31 (57)	83	2.4	3.9	63 (67)	22 (23)	95	2.2	2.2	38 (49)	26 (34)	77
Treatment-3															
Ludhiana-1	3.8	3.6	29 (48)	24 (40)	61	4.4	4.4	54 (62)	24 (27)	87					
Nadia	1.4	1.1	5 (19)	20 (76)	26	0.8	0.6	2 (12)	15 (76)	19					
Ludhiana-3	2.1	3.7	28 (45)	31 (50)	62	1.3	2.1	11 (25)	24 (53)	44					
Palampur	3.5	3.7	34 (58)	18 (30)	59	2.5	4.1	60 (69)	19 (22)	87					
Ludhiana-2	6.1	6.0	71(71)	26 (26)	101	2.5	2.2	10 (23)	20 (46)	45					
Karnal	3.0	4.3	32 (46)	35 (49)	70	1.3	2.2	9 (20)	26 (56)	46					
Samastipur	1.8	1.7	4 (12)	26 (82)	32	1.5	1.2	3 (12)	21 (79)	27					
Pantnagar	3.6	2.1	6 (16)	29 (77)	38	1.6	1.4	3 (8)	27 (81)	33	2.0	2.5	3 (9)	27 (77)	35
Barrackpore	1.5	1.9	2 (7)	25 (80)	32	0.8	1.3	4 (15)	19 (70)	28	1.0	1.2	8 (24)	22 (65)	34

Obs.Y: Observed yield; Sim.Y: Simulated yield; N_{Inorg}: crop uptake from inorganic N sources; N_{SOM}: N uptake by mineralization of SOM; N_{uptake}: total crop N uptake.

* Third crop refers to cowpea in Pantnagar and jute in Barrackpore.

† Except observed yield, all the results belong to the model calculations.

** In parenthesis values are shown as the % of total N uptake

†† N uptake from fresh organic sources = N_{uptake}-($N_{Inorg.}$+ N_{SOM}).

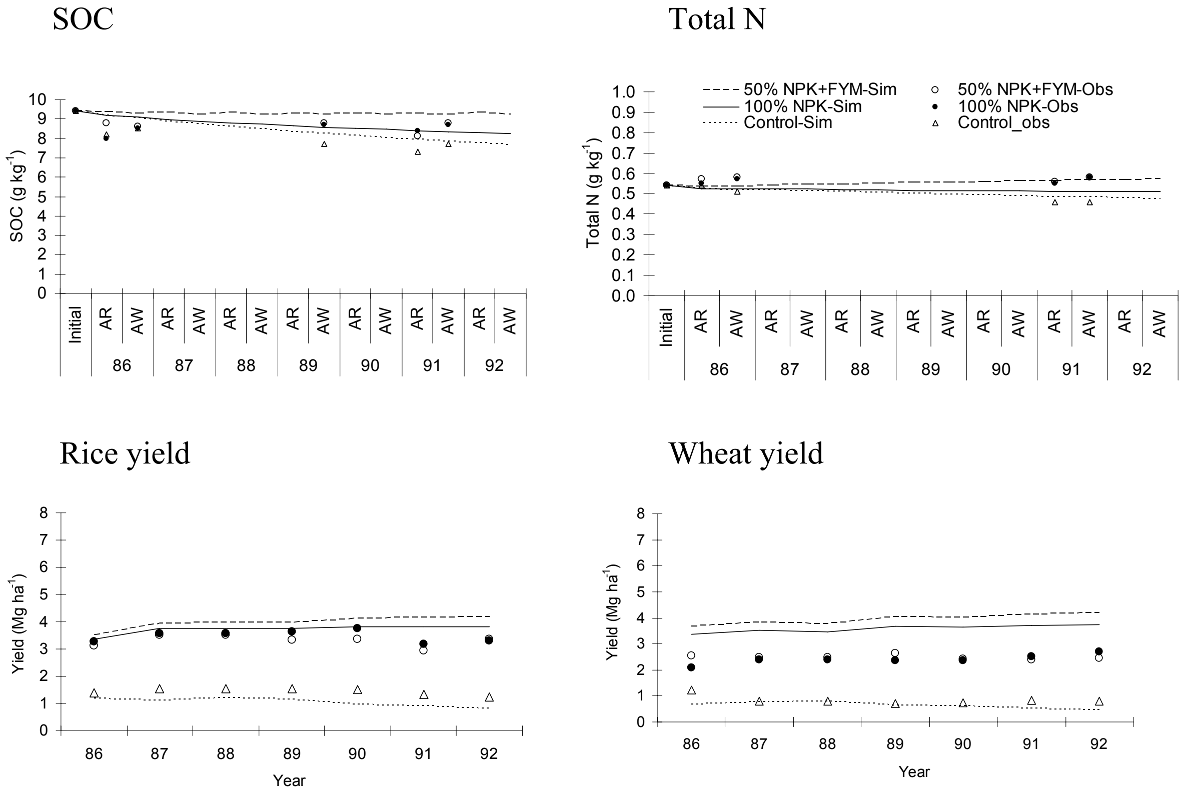


Figure 5. Comparison of simulation results and experimental data for Nadia for different treatments.

lower than observed (0.8 Mg ha^{-1}), where 76% of N uptake is from SOM compared to 37% under 100% NPK.

Validation

Model results for Ludhiana-3 of SOC show an increasing trend, similar to the observations (Figure 6) in Treatment-1 (50% NPK+ 50% FYM) and Treatment-2 (100% NPK). For the control, the model does not reproduce the observed increase. Prior to rice-wheat, this site was under a maize-wheat cropping system (Singh, Punjab Agricultural University, Ludhiana, pers.comm). Large amounts of GM were applied in this land use system, which might have led to a low C/N ratio such as 5.7 at this site. Green manure application may lead to a microbial community dominated by bacteria. Since the C/N ratio of bacteria is lower, the C/N ratio of the organic matter transferred to the labile pool may be lower than the value of 10 set in the model, which could be a reason that total N is underestimated by the model for all treatments (Figure 6). When the C/N ratio of the labile pool in the model was changed to 5, total-N more closely followed the observations (results not shown).

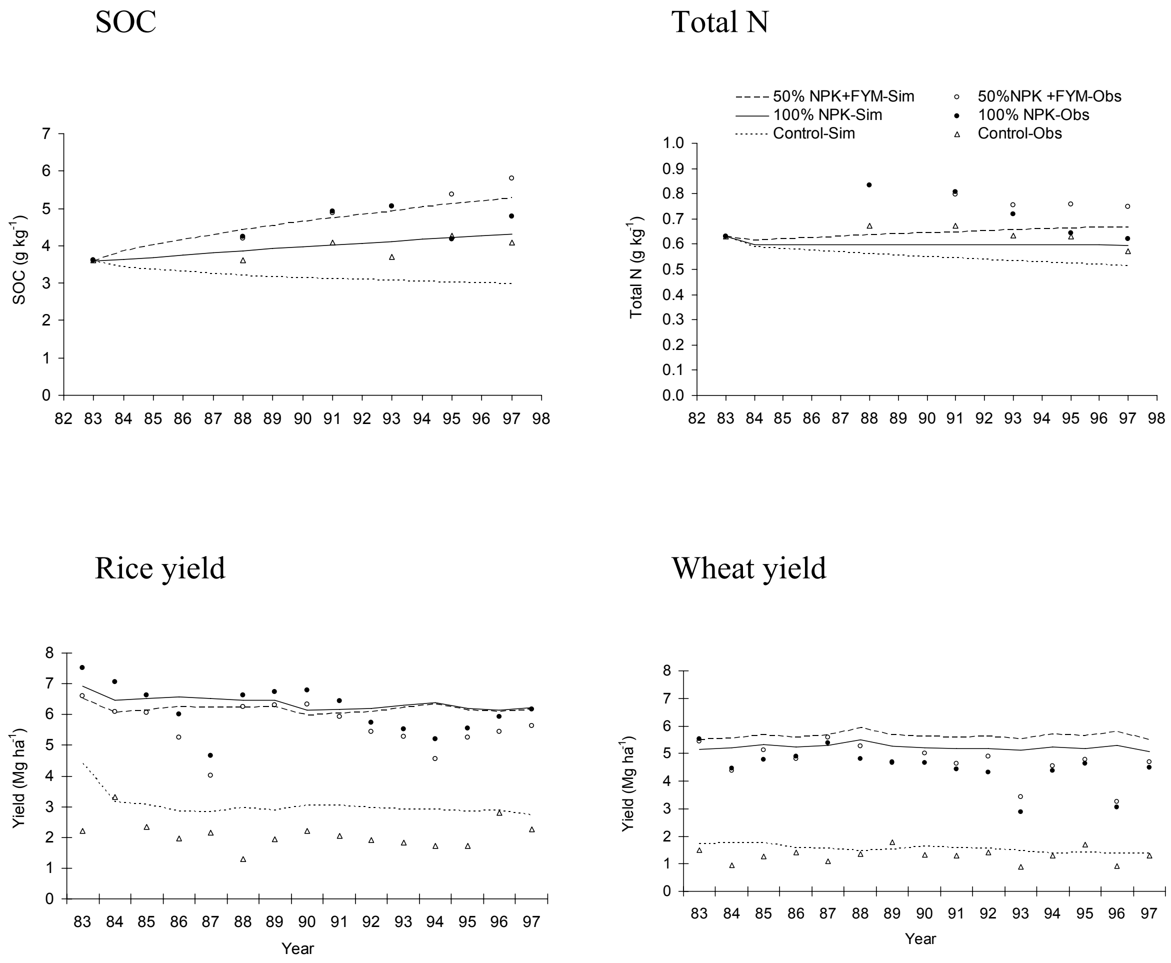


Figure 6. Comparison of simulation results and experimental data for Ludhiana-3 under different treatments.

Simulated yields for rice and wheat are in line with the observed values, except for the control treatment in rice where it is strongly overestimated by the model. In Treatments 1 and 2, observed rice yields declined in the first five years, which is not reproduced by the model. In rice, similar to Ludhiana-1, organic sources contributed more than 50% to total N uptake in Treatments 1 and 3, compared to 40% in Treatment-2 where 100% N is applied as mineral fertilizer. In wheat, the contribution from organic sources is lower (35-37%) in Treatments 1 and 2 and higher in the control (75%).

For Palampur, the model results showed an increase in SOC, stronger with increasing lantana (*Lantana camera*) additions, similar to the observations, but the model underestimated the rate of increase (Figure 7). Overall, N dynamics showed the same picture. Simulated yields for both rice and wheat are fluctuating, similar to the observations, which is related to annual variations in solar radiation. A decrease in N-

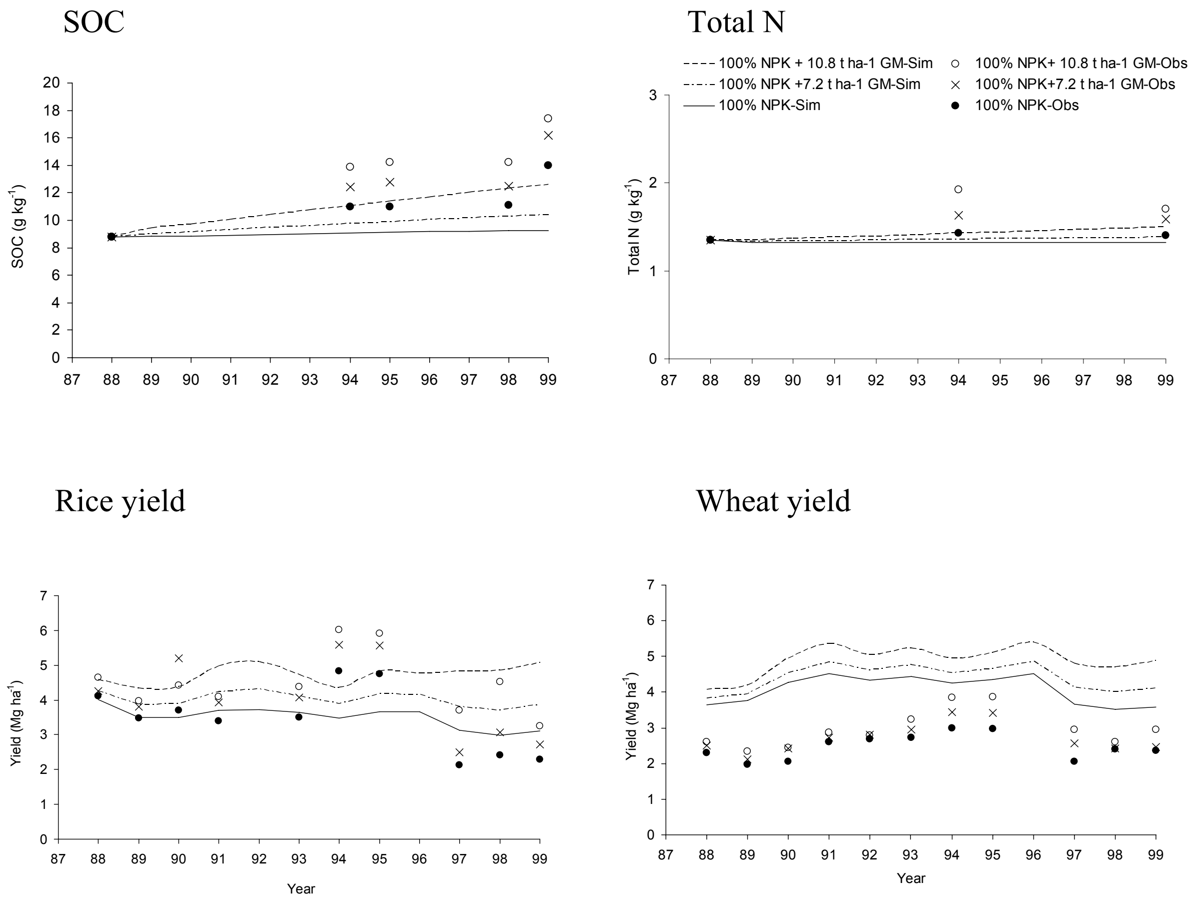


Figure 7. Comparison of simulation results and experimental data for Palampur under different treatments.

fertilizer application rate (from 100% to 66% of recommended N) (Sharma et al.,2003) is the reason for the decrease in yields after 1996. Average N supply without organic manure addition (Treatment-3) is low in Palampur, despite a relatively high initial SOC, which is increasing over the years. The average contribution from SOM is 18 kg N ha^{-1} in rice and 19 in wheat (Table 4). The low seasonal average temperature at this site (Figure 2) is the reason for the low mineralization rate.

For Ludhiana-2, though the model reproduced the increase in SOC with rice straw incorporation, contrary to the treatment with straw removal (Figure 8), the rate of increase is underestimated. Simulated yields for both crops compare well to the observations in all three treatments (Figure 9). Mineralization contributes 20-26 kg N ha^{-1} to crop uptake (in the control treatment), even though SOC is relatively low (~4 g kg^{-1}), because of higher mean daily temperature (Table 4).

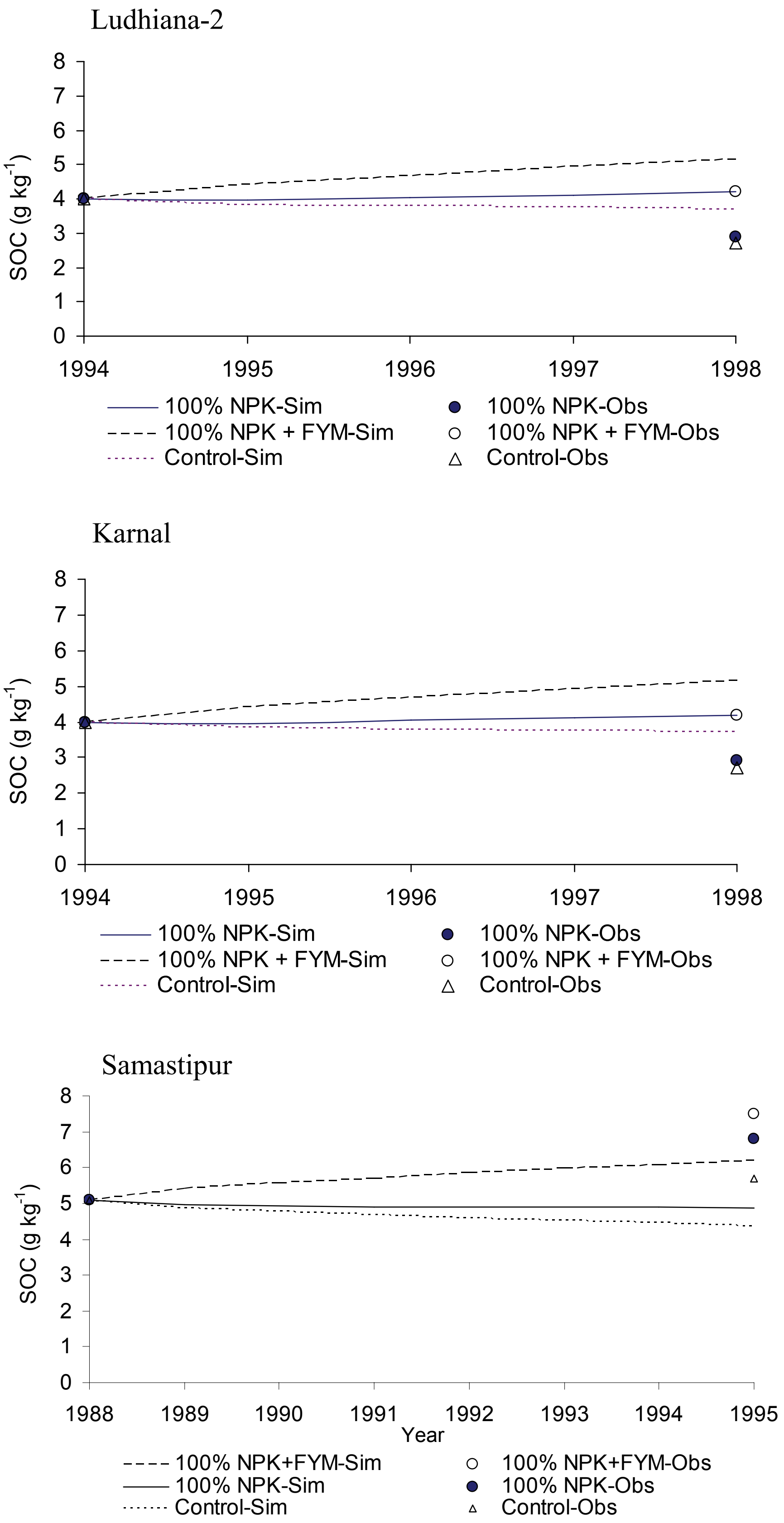


Figure 8. Comparison of simulation results and experimental data for soil organic carbon under different treatments at various sites in the IGP.

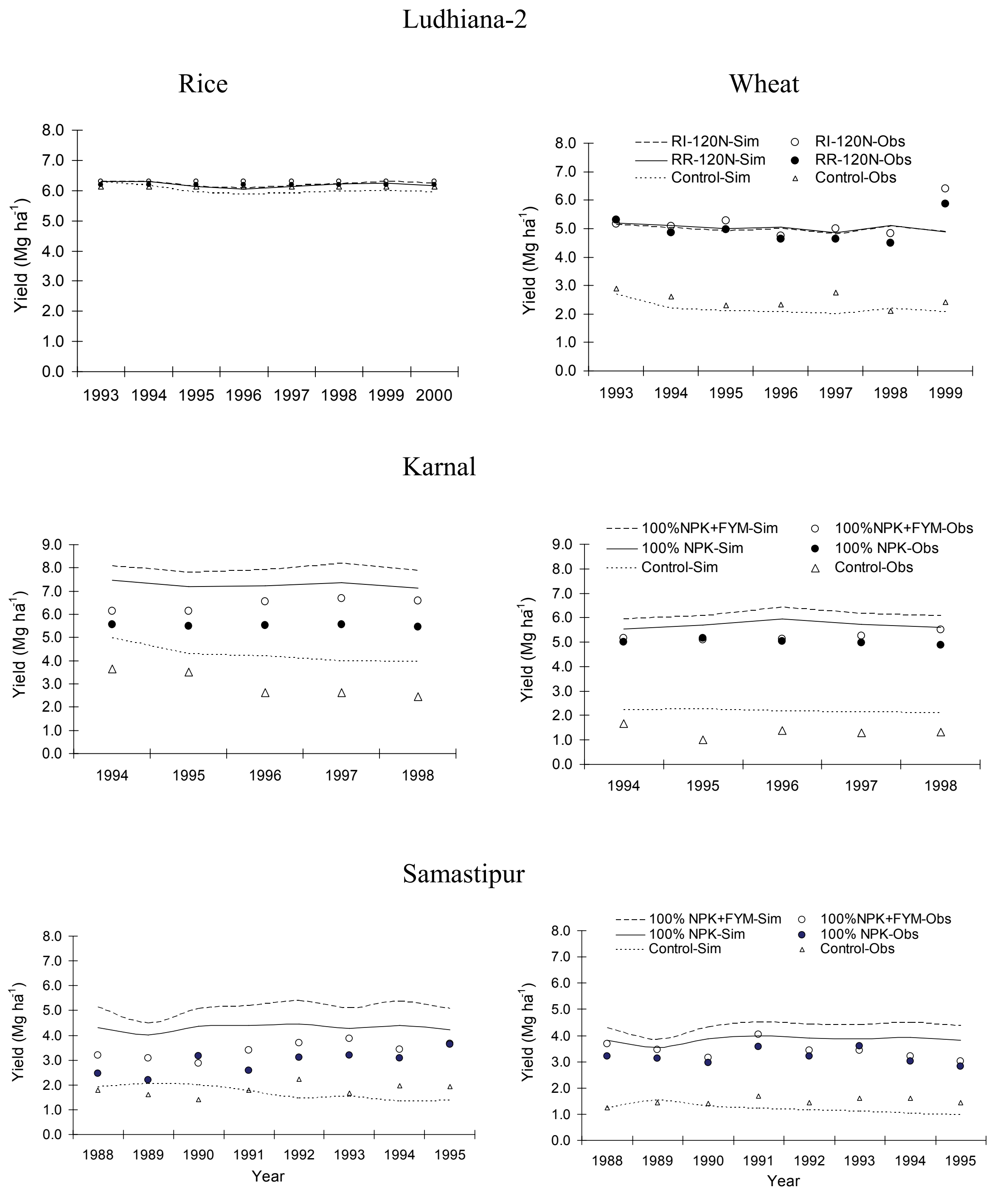
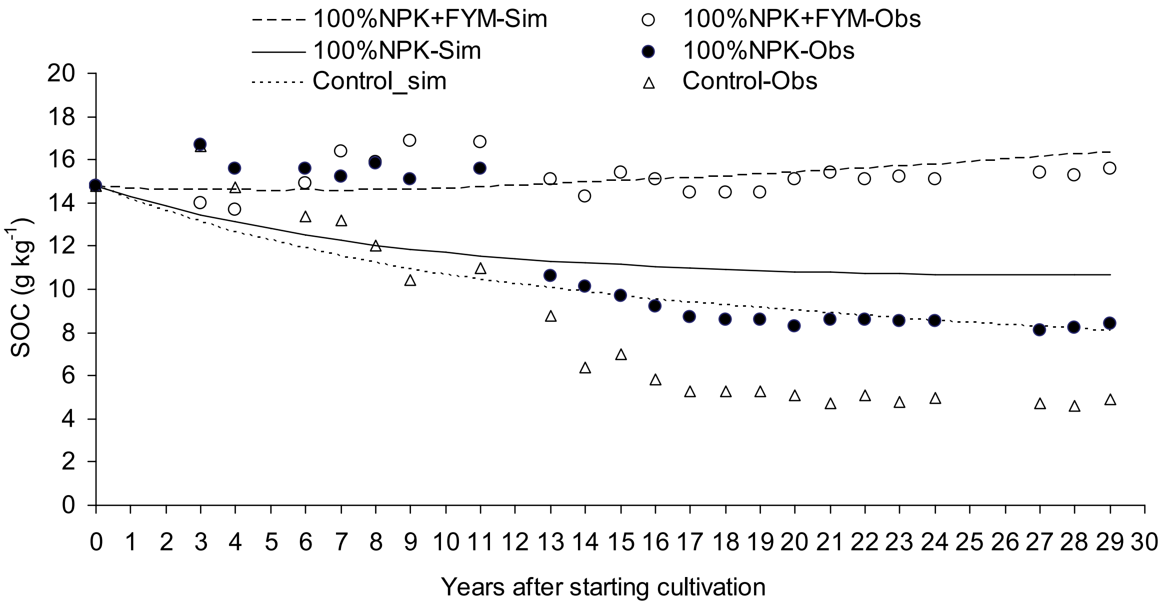


Figure 9. Comparison of simulation results and experimental data for rice and wheat yields under different treatments at various sites in the IGP.

For Karnal, simulated SOC is overestimated (Figure 8) in all the treatments. Similarly, crop yields are also overestimated in all treatments (Figure 9). The disparity between model results and observations could be due to the sodic nature of the soil, leading to

Pantnagar



Barrackpore

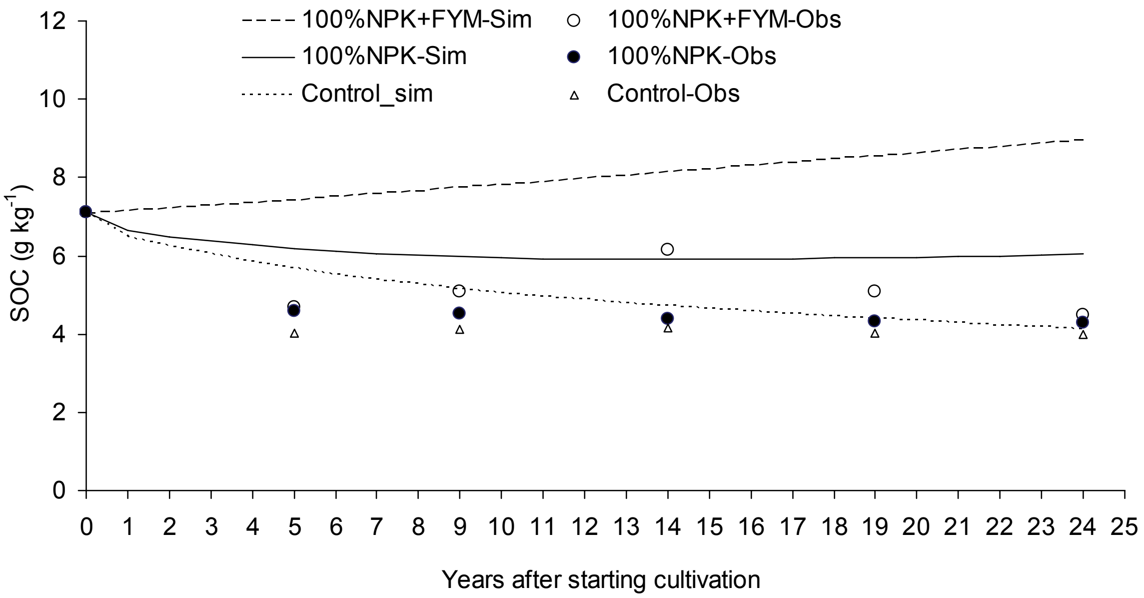


Figure 10. Comparison of simulation results and experimental data for SOC under different treatments in Pantnagar and Barrackpore.

chemical hydrolysis of SOC, making it more accessible to microorganisms (Laura, 1973; Chander et al., 1994; Wong et al., 2004). Similar to Ludhiana, N from inorganic (mainly irrigation) sources is a major contributor to total N uptake (Table 4), especially in rice in the control.

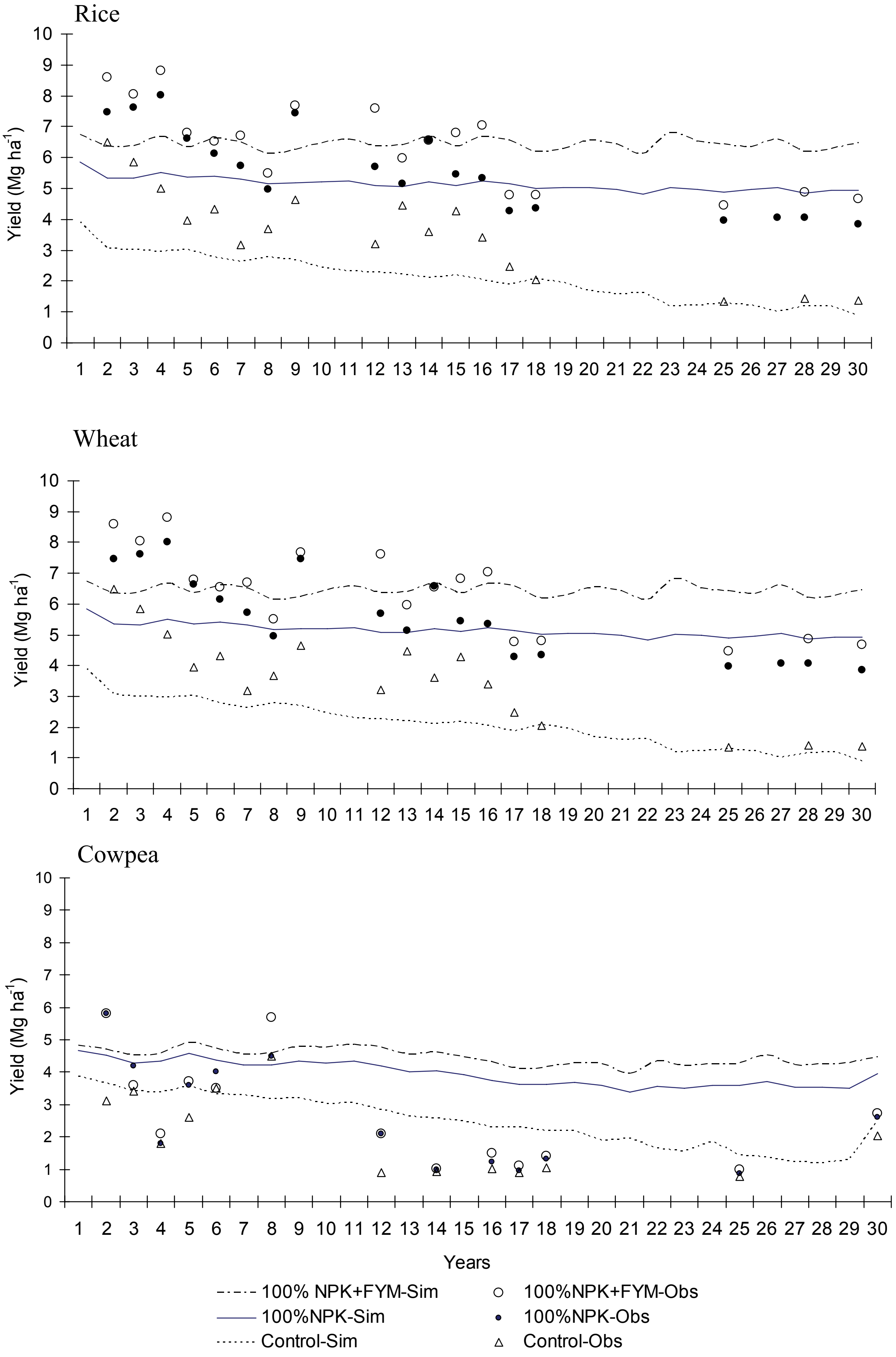


Figure 11. Comparison of simulation results and observed data for crop yields under different treatments in Pantnagar.

Similar to Karnal, simulated SOC for Samastipur is overestimated in all three treatments (Figure 8). The calcareous nature of the soil here (high Soil Inorganic Carbon (SIC) content) may have led to organic carbon protection (Chapter 3). Simulated rice and wheat yields are also overestimated (Figure 9). The reason for the overestimated yields in Samastipur with an underestimation of SOC, in contrast to Karnal where the overestimated yields are associated with overestimated SOC contents is not clear. A nitrogen supply of 20-26 kg ha^{-1} from SOM results in rice and wheat yields of 1.7 and 1.2 Mg ha^{-1}, compared to observed values of 1.8 and 1.5 (Table 4).

Simulated SOC dynamics for Pantnagar and Barrackpore, where the soils were under natural vegetation before the experiments started, showed a decline in SOC under cultivation for treatments without organic residue additions (Treatments-2 and 3) and an increase with FYM addition (Treatment 1), although the simulated rates of decomposition appear too low (Figure 10). For both locations, the model simulated the declining trends in rice yields, similar to the observations (Figures 11 and 12). For Pantnagar, the model underestimated rice yields in the initial years in all treatments. Towards the end of the simulation period, yields in Treatment-1 and Treatment-2 are overestimated, whereas the control treatment followed the observations. However, wheat yields are satisfactorily simulated by the model in all treatments. For Barrackpore, the model simulated rice yields satisfactorily, even though they are overestimated in the last years of simulation. Wheat yields are in general overestimated by the model in all treatments. Jute yields are also well simulated in all treatments. For Pantnagar, average N supply from SOM in the control treatment is about 30 kg ha^{-1}, sufficient for yields of 2.1 and 1.4 Mg ha^{-1} for rice and wheat, respectively (Table 4). For Barrackpore, N-release under rice (25 kg N ha^{-1}) is higher than under wheat (19 kg N ha^{-1}), leading to a yield of 1.9 Mg ha^{-1} compared to a wheat yield of 1.3 Mg ha^{-1}.

The model results of methane emission cannot be validated, as no observations are available for methane in these LTEs. The model results in general show that methane emission increases (Figure 13) with increasing biomass production and residue application in rice. Sites in Ludhiana (Ludhiana-1, Ludhiana-2 and Ludhiana-3) and Karnal show higher methane emission (~ 200 kg ha^{-1}) for rice even without any residue addition, associated with higher yields. As the model assumes no methane emission in an aerobic crop, there is no impact of rice residue incorporation on wheat in Treatment-1 in Ludhiana-2 (Figure 13). In Pantnagar, a high rate of FYM addition (15 Mg ha^{-1}) in rice contributes to higher emission (760 kg ha^{-1}) compared to mineral

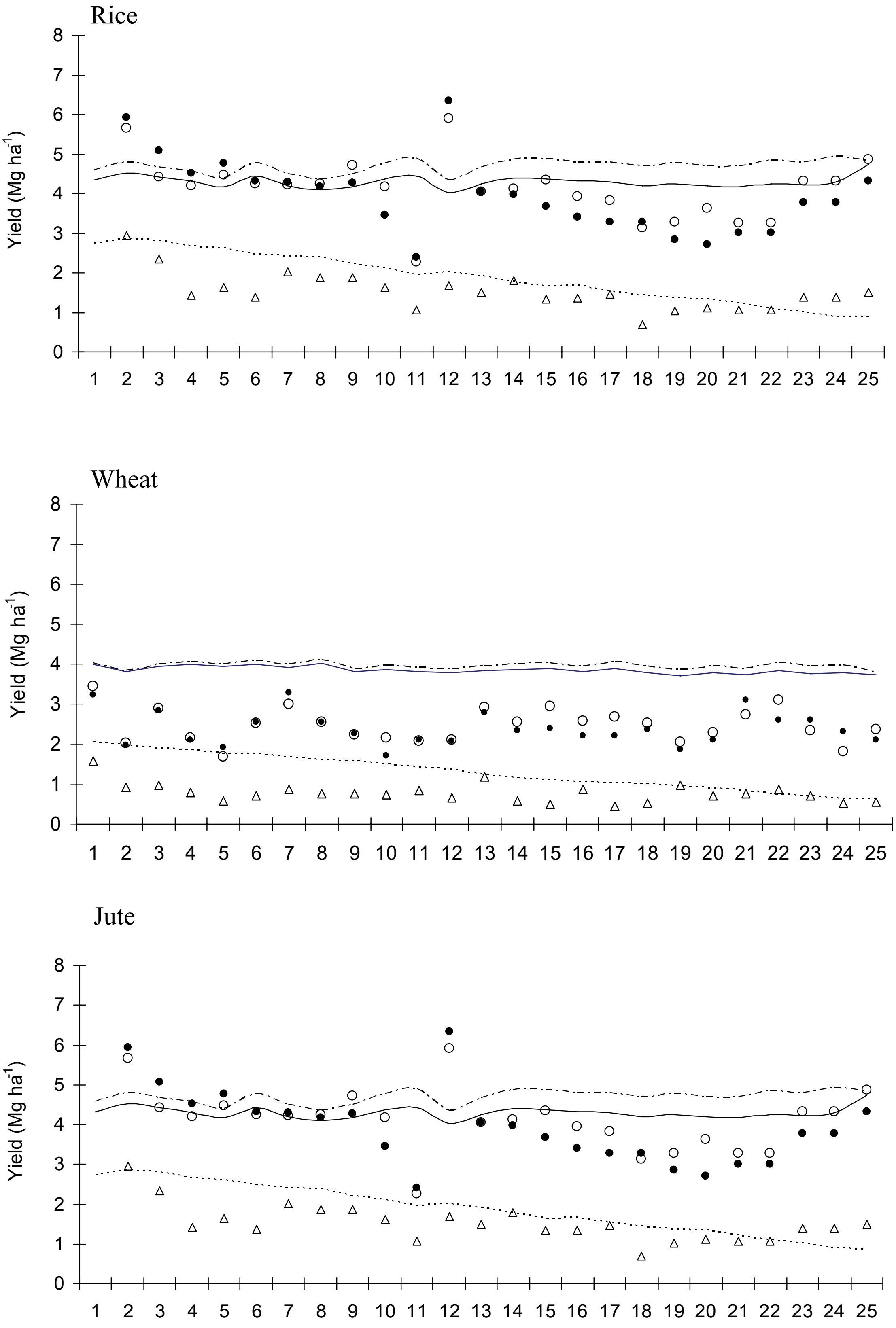


Figure 12. Comparison of simulation results and experimental data for crop yields under different treatments in Barrackpore.

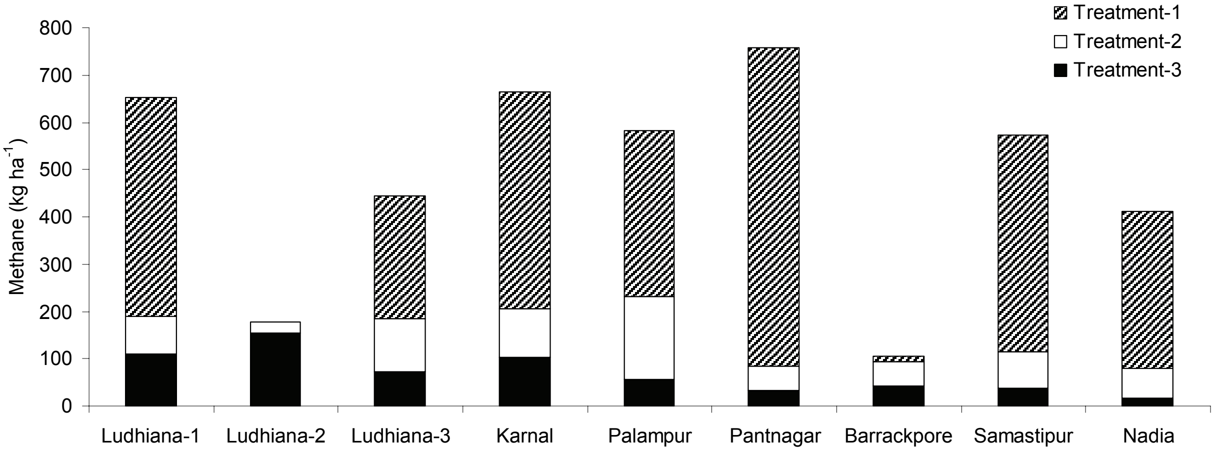


Figure 13. Model results of long-term average seasonal methane emissions in rice under different treatments at various sites of the IGP (See Table 2 for treatment details).

fertilizers only (80 kg ha^{-1}). The low rate of methane emission in Barrackpore with addition of 10 Mg ha^{-1} of FYM is because the FYM is added to the jute crop.

Goodness of fit of the model results show a Root Mean Square Deviation (RMSD[3]) of 1.9 g kg^{-1} for SOC, which is 23% of the mean value of SOC for the whole dataset (Figure 14). Rice and wheat yields show an RMSD of 1.1 Mg ha^{-1} for both, which is 26% and 37% of the mean observed yield for the entire dataset. Simulation results show a high correlation ($r^2 = 0.9$) for rice yields with total solar radiation and N uptake in the 100% NPK treatments (Figure 15). For the non-fertilized treatments, the relation is weaker, as yield is determined by nutrient availability rather than solar radiation. On the other hand, the correlations of yield with SOC content and N supply from SOM are weak even in the non-fertilized treatments.

Model application

Trend analysis of crop yield and yield determining factors

Analysis of trends (slopes) of crop yields and associated climate (e.g. radiation) and soil (e.g. SOC, total-N) parameters over time may contribute to insight in changes in

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[3] $$\text{RMSD} = \left[\frac{\sum_{i=1}^{n} (Y_i - O_i)^2}{n} \right]^{0.5}$$ where Y_i and O_i are simulated and observed values, respectively.

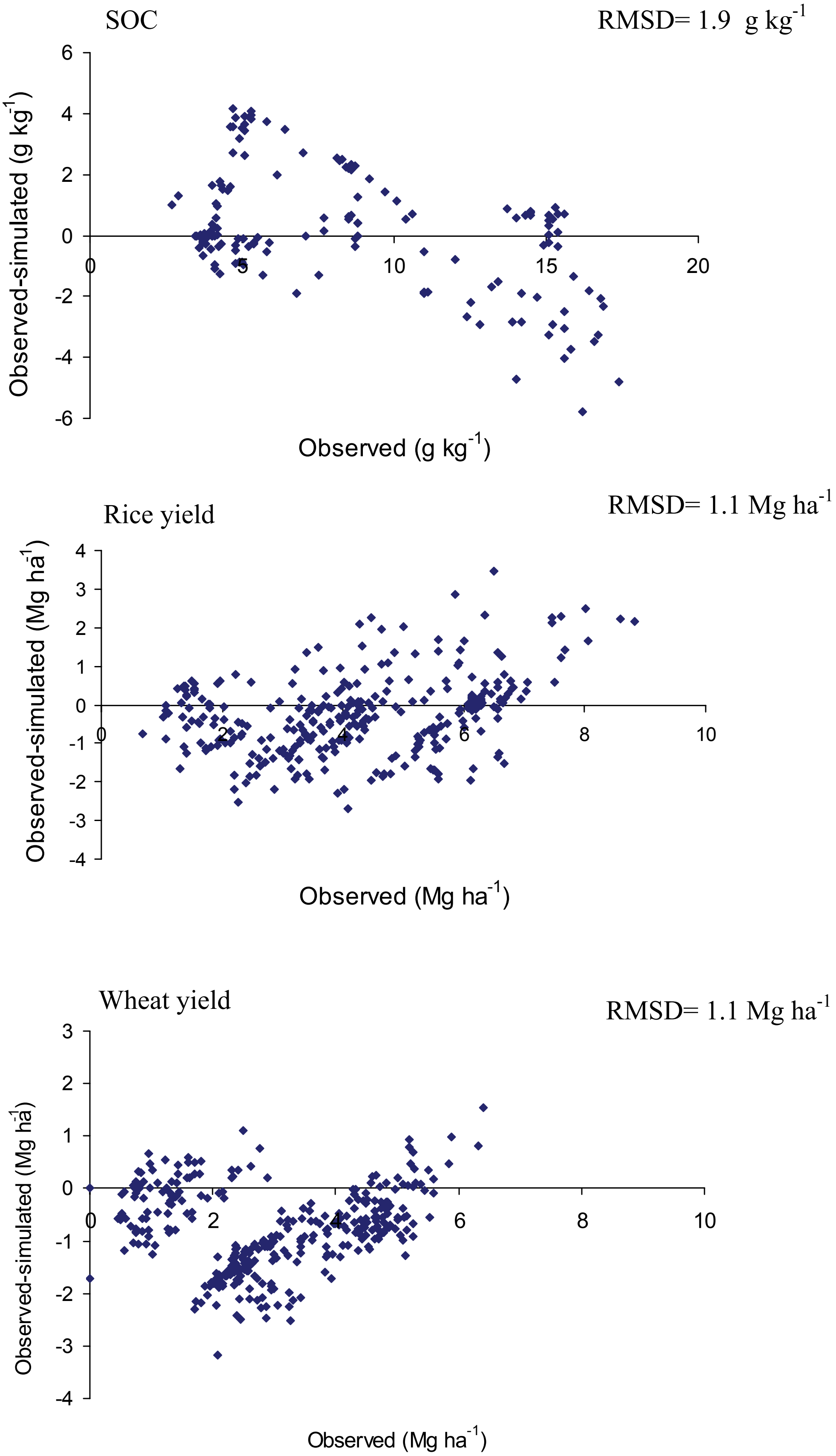


Figure 14. Comparison of the model results with the observed for the whole dataset (RMSD is the root of mean of square of deviation of the simulated result from the observed result).

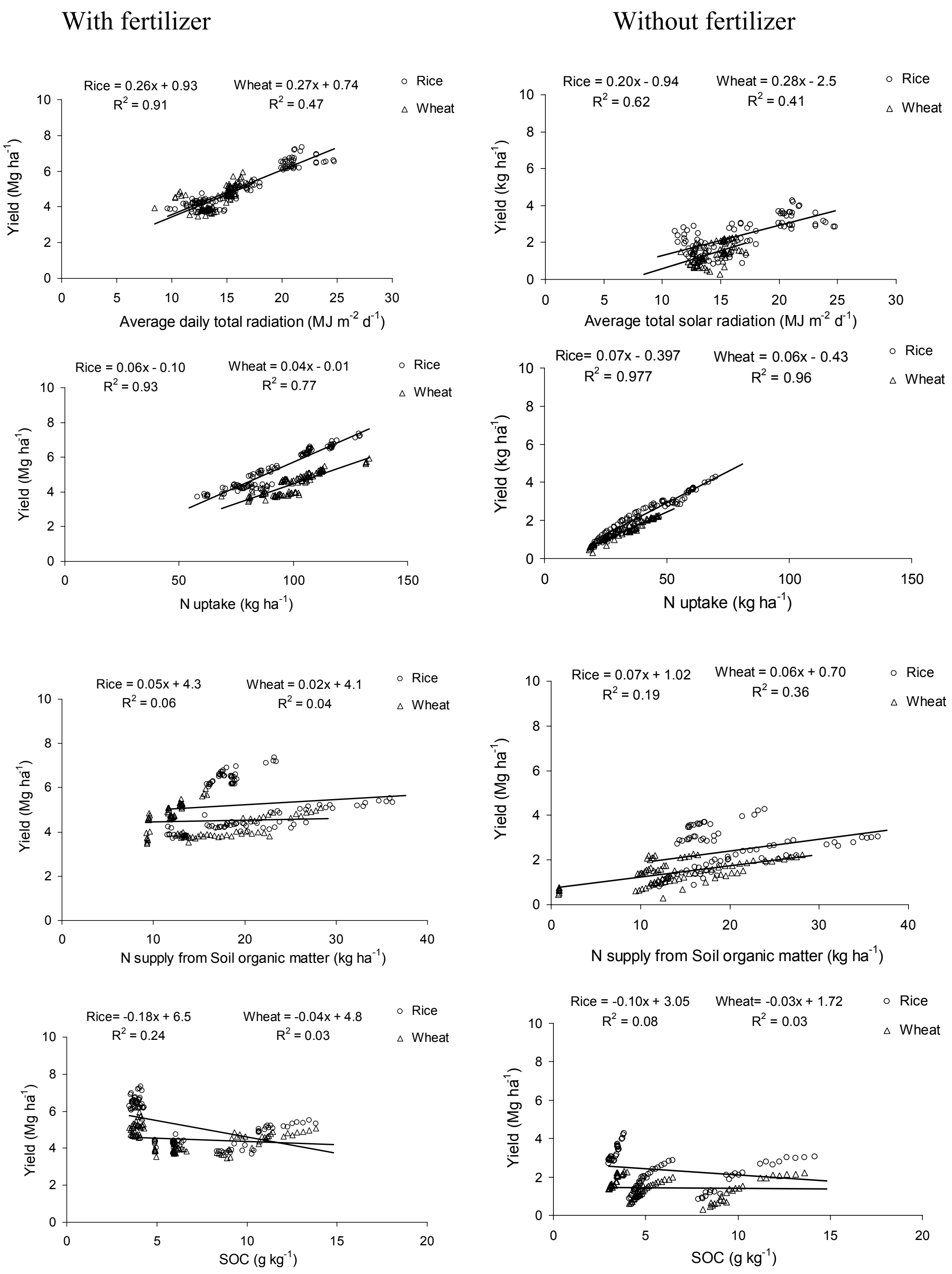


Figure 15. Correlation of simulated crop yields with radiation, N uptake, N supply from soil organic matter and SOC content.

yield in relation to changes in various system characteristics. A trend analysis of model results with changes in radiation, SOC, nitrogen, and yield and their interactions was performed, using simple linear regression. Observed results were subjected to a similar analysis to compare these trends and to examine the factors responsible for yield change at these sites over time. Statistical significance is determined by *P* values using Microsoft EXCEL on slopes that indicate the level of significance of these changes.

Observed and simulated trends in yields in the different treatments for the various sites show that only in Ludhiana-3 and Pantnagar there is a statistically significant decline in the treatment with recommended NPK application (Table 5). In Ludhiana, a significant decline in rice yield in the mineral fertilizer treatment (Treatment-2) is observed only in Ludhiana-3, whereas the simulated results show a significant decline in all treatments. Observed wheat yield also shows a significant decline in Treatment-1 and Treatment-2, but the simulated decline in Treatment-2 is smaller (-0.02 Mg ha^{-1} y^{-1}; $P<0.05$) than observed (-0.10 Mg ha^{-1} y^{-1}; $P<0.05$). Soil organic carbon changes in all three sites in Ludhiana (Ludhiana-1, Ludhiana-2, and Ludhiana-3) are positive in Treatment-1 and Treatment-2, and of similar magnitude for the observations and the simulations (Table 5). Total-N shows a significant decline in Treatment-2 in Ludhiana-3. A trend of decreasing solar radiation (Table 6) may be one of the reasons for such a decline in rice and wheat yields at this site. However, solar radiation and crop yield are not significantly correlated (Table 7). None of the tested yield determining factors is significantly correlated to yield in Ludhiana-3, in none of the treatments, neither observed nor simulated.

In Karnal, observed rice yields show a positive trend (Table 5; 0.14 Mg ha^{-1} y^{-1}; $P< 0.05$) in Treatment-1 and a negative trend in the control (–0.33 Mg ha^{-1} y^{-1}; $P< 0.05$). The model results show a decline only in the control treatment (–0.24 Mg ha^{-1} y^{-1}; $P< 0.05$). Observed wheat yields do not show any significant trend of decline in any of the treatments, whereas simulated yields show a negative change (–0.04 Mg ha^{-1} y^{-1}; $P< 0.05$) in the control. Simulated soil organic carbon shows an increasing trend (0.05 g kg^{-1} y^{-1}; $P< 0.05$) in the recommended NPK treatment, in contrast to a decline in the observed values (Figure 8).

In Palampur, neither observed nor simulated rice and wheat yields shows any significant trend in any of the treatments, except for simulated wheat yield in the control (–0.03 Mg ha^{-1} y^{-1}; $P< 0.05$) (Table 5). However, SOC shows a clear increasing trend in all treatments, both observed and simulated, although the slope

Table 5. Trends in change in observed and simulated yield, SOC and total soil-N under different treatments at various sites in the IGP.

Site	Slope							
	Rice yield (Mg ha^{-1} y^{-1})		Wheat yield (Mg ha^{-1} y^{-1})		SOC (g kg^{-1} y^{-1})		Total N (g kg^{-1} y^{-1})	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
Treatment-1								
Ludhiana-1	-0.13	0.00	0.05	0.02*	0.18*	0.18*	-	0.008*
Ludhiana-2	-	0.02	0.10	-0.01	0.21*	0.19*	-	0.008*
Ludhiana-3	-0.06	-0.04*	-0.08*	-0.01	0.16*	0.12*	0.008	0.000
Karnal	0.14*	-0.01	0.09	0.03	-	0.28*	-	0.005
Palampur	-0.03	0.04	0.07	0.04	0.67*	0.49*	0.034	0.001
Samastipur	0.08*	0.04	-0.07	0.04	-	0.11*	-	0.004*
Pantnagar	-0.13*	0.00	0.03	0.00	0.01	0.06*	-	0.00*
Barrackpore	-0.04	0.01*	0.00	0.00	-0.07	0.08*	-	0.00*
Nadia	-0.02	0.09*	-0.02	0.08*	-0.06	-0.03	0.005	0.002
Treatment-2								
Ludhiana-1	-0.09	-0.02	0.07	0.00	0.05*	0.05*	-	-0.001
Ludhiana-2	-	0.00	0.02	-0.03	0.04*	0.08*	-	0.001
Ludhiana-3	-0.09*	-0.07*	-0.10*	-0.02*	0.07	0.06*	-0.004	-0.005*
Karnal	-0.02	-0.06	-0.05	0.02	-	0.05*	-	-0.008
Palampur	-0.13	0.02	0.02	0.00	0.55*	0.22*	0.022	0.003
Samastipur	0.13*	0.01	-0.02	0.02	-	-0.02*	-	-0.005*
Pantnagar	-0.13*	-0.02*	-0.02	-0.02*	-0.36*	-0.12*	-	-0.012*
Barrackpore	-0.08*	0.00	-0.01	-0.01*	-0.09	-0.11	-	-0.008*
Nadia	-0.02	0.06	0.07*	0.06*	-0.07	-0.17*	-0.004	0.001
Treatment-3								
Ludhiana-1	-0.02	-0.03*	0.06	-0.01	0.02*	0.00	-	-0.004*
Ludhiana-2	-	-0.03	-0.07	-0.06	0.04	0.02	-	-0.003
Ludhiana-3	-0.02	-0.09*	0.00	-0.06*	0.04	-0.03*	-0.004	-0.008*
Karnal	-0.33*	-0.24*	-0.05	-0.04*	-	-0.07*	-	-0.014*
Palampur	-0.13	0.00	0.02	-0.03*	0.37*	0.08*	0.004	-0.002
Samastipur	0.04	-0.08*	0.03	-0.06*	-	-0.07*	-	-0.008*
Pantnagar	-0.15*	-0.08*	-0.04*	-0.07*	-0.45*	-0.20*	-	-0.017*
Barrackpore	-0.04*	-0.09*	-0.01*	-0.06*	-0.09	-0.06*	-	-0.013*
Nadia	-0.03	-0.06*	-0.05	-0.05*	-0.27	-0.26*	-0.009	-0.017

*Slopes within observations or simulations are significant at $P<0.05$.

Table 6. Change (slope) in average daily solar radiation ((MJ m^{-2} d^{-1}) y^{-1}) over time at different sites in the IGP.

Site	Rice	Wheat
Ludhiana-1	-0.16	-0.09
Ludhiana-2	0.02	-0.11*
Ludhiana-3	-0.33*	-0.10*
Karnal	-0.08	-0.04
Palampur	0.13	0.30*
Samastipur	0.08	0.03
†Pantnagar	-0.01	0.00
†Barrackpore	0.03	-0.01
†Nadia	0.13	0.24*

† Weather data source: NOAA (www.NOAA.org). For Barrackpore and Nadia radiation is generated from weather data of Kolkota by using the program *RadEst 3* (Donatelli and Bellocchi, 2003).

* Slopes of radiation for rice and wheat are significant at $P<0.05$.

(Table 5) is higher for the observations. Solar radiation shows a clear trend of increase ((0.30 MJ m^{-2} d^{-1}) y^{-1}; $P<0.05$) over the period examined (Table 6), which however, is not reflected in the yields that show a decrease (Figure 7) as a result of a reduction (by 1/3rd) in N fertilizer application rate during the last three years of cultivation.

For Samastipur, observed rice yields show an increase in all treatments that is significant for Treatment-1 (0.08 Mg ha^{-1} y^{-1}) and Treatment-2 (0.13 Mg ha^{-1} y^{-1}), whereas simulated yields do not show significant changes for Treatment-1 and Treatment-2, and a decrease in the control (–0.08 Mg ha^{-1} y^{-1}; $P< 0.05$). In the control, simulated wheat yields also show a significant decrease (–0.06 Mg ha^{-1} y^{-1}). In the simulation, SOC shows an increase in Treatment-1 (0.11 g kg^{-1} y^{-1}; $P< 0.05$) and a decline in Treatment-2 (–0.02 g kg^{-1} y^{-1}; $P< 0.05$) and Treatment-3 (–0.07 g kg^{-1} y^{-1}; $P< 0.05$), in contrast to a generally increasing trend in the observations (Figure 8).

In Pantnagar, observed rice yields show a significant declining trend in all treatments (Table 5). Model results do not show any decline in Treatment-1, and a lower rate of decline in Treatment-2 (–0.02 Mg ha^{-1} y^{-1}; $P< 0.05$) and Treatment-3 (–0.08 Mg ha^{-1} y^{-1}; $P< 0.05$) than observed (–0.13 and –0.15 Mg ha^{-1} y^{-1}, respectively). On the other hand, observed wheat yields did not show any significant change in any of the treatments except the control (–0.04 Mg ha^{-1} y^{-1}), whereas the simulated values show a

Table 7. Change in crop yield with respect to different soil and climatic factors for observed and simulated results for different treatments in various sites of the IGP.

Site	Rice yield change with respect to						Wheat yield change with respect to					
	Radiation (Mg ha^{-1}/ MJ m^{-2} d^{-1})		SOC (Mg ha^{-1}/ g kg^{-1} SOC)		Total N (Mg ha^{-1}/ g kg^{-1} N)		Radiation (Mg ha^{-1}/ MJ m^{-2} d^{-1})		SOC (Mg ha^{-1}/ g kg^{-1} SOC)		Total N (Mg ha^{-1}/ g kg^{-1} N)	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
						Treatment-1						
Ludhiana-1	0.34	0.13	-0.68	-0.03	-	1.06	-0.18	-0.05	0.11	0.09*	-	2.10*
Ludhiana-2	-	0.12	-	0.11	-	3.42	0.33	0.12	-0.12	-0.06	-	-0.04
Ludhiana-3	0.01	0.10	-0.57	-0.31	-6.2	-8.15	0.10	0.11	-0.47	-0.08	-6.3	-6.33
Karnal	-0.11	0.20	-	-0.04	-	3.38	-0.07	0.17	-	0.13	-	-2.50
Palampur	-0.21	0.27*	-0.11	0.12	1.8	2.73	0.11	0.21*	0.06	0.15	2.08	2.89
Samastipur	0.10	0.19*	-	0.31	-	11.3	0.09	0.25*	-	0.28	-	9.63
Pantnagar	0.23	0.21*	-0.18	-0.03	-	-1.49	0.55	0.17*	-0.06	0.013	-	-0.06
Barrackpore	-0.49*	0.23*	0.42	0.14*	-	16.6	0.19	0.13*	0.44*	-0.04	-	-5.88
Nadia	0.06	0.17	-0.46	-3.3*	12.7	15.4	-0.05	0.30*	0.10	-4.43*	-	1.46*
						Treatment-2						
Ludhiana-1	0.24	0.13*	-1.26	-0.33	-	12.4*	-0.33	-0.01	1.93*	-0.10	-	-1.91
Ludhiana-2	-	0.08	-	-0.04	-	5.4	-0.95	0.24	-3.71	-0.41	-	4.5
Ludhiana-3	0.08	0.16	-0.87	-1.14	0.33	16.4	0.51	0.15	-1.29	-0.37	-1.6	3.98
Karnal	0.05	0.21	-	-0.54	-	7.02	0.13	0.14	-	-0.15	-	-5.12
Palampur	-0.52	0.13*	-0.20	0.10	0.88	2.73	0.07	0.10	0.04	0.07	-1.0	-2.14
Samastipur	0.06	0.08*	-	-0.47	-	-1.87	0.10	0.16*	-	-0.62	-	-2.76
Pantnagar	0.12	-0.02*	0.30*	0.16*	-	1.86*	-0.5	0.08	-0.01	0.13*	-	1.55*
Barrackpore	-0.75*	0.14*	0.84*	0.13	-	0.21	-0.02	0.15*	0.39*	0.16*	-	1.09*
Nadia	-0.11	0.11	-0.37	-0.4*	12.7	8.64	-0.05	0.30*	0.09	-0.5*	-	-30*
						Treatment-3						
Ludhiana-1	0.17	0.06	-1.41	1.80	-	8.61*	-0.12	-0.02	1.63	-1.1*	-	0.54
Ludhiana-2	-	0.12	-	0.97	-	11.9	-0.09	0.48	0.16	-1.33	-	21.5*
Ludhiana-3	0.03	0.16	0.32	3.5	-6.0	11.1	0.01	0.20	0.37	1.96	-0.2	6.05
Karnal	0.32	0.50	-	3.6*	-	16.2*	-0.11	0.09	-	0.46	-	1.86
Palampur	-0.43	0.04	-0.38	-0.08	4.36	16.3*	0.08	0.03	-0.00	-0.37	8.0	-22.9
Samastipur	0.14*	-0.11	-	1.0*	-	8.8*	0.01	-0.13	-	0.53*	-	4.6*
Pantnagar	0.02	0.09	0.22*	0.38*	-	4.81*	-0.5	-0.18	0.04	0.31*	-	4.1*
Barrackpore	-0.23	-0.4*	0.20	0.75*	-	6.38*	-0.2	0.20	0.31*	0.54*	-	4.5*
Nadia	-0.07	-0.16	0.02	0.24*	-0.8	6.6*	-0.13	-0.2*	0.26	0.18*	-	5.8*

* Significant at $P<0.05$.

significant decline in Treatment-2 (–0.02 Mg ha^{-1} y^{-1}) and in the control (–0.07 Mg ha^{-1} y^{-1}). Soil organic carbon shows an increasing trend in the simulation in Treatment-1 (0.06 Mg ha^{-1} y^{-1}; $P < 0.05$), which is not significant in the observations. In Treatment-2 and the control, a significant decline in SOC is found in both the observations and the simulations (Table 5). Simulated results of total-N follow the trends of SOC. Rice yield in Treatment-1 is significantly positively correlated to solar radiation (Table 7). For Treatment-2 and Treatment-3, yields are significantly positively correlated to SOC and total-N, that significantly decline in these two treatments, both for the observed and for the simulated results.

Observed rice yields in Barrackpore show a declining trend that is statistically significant for Treatment-2 (–0.08 Mg ha^{-1} y^{-1}) and Treatment-3 (–0.04 Mg ha^{-1} y^{-1}) (Table 5). Model results show a marginally increasing trend in Treatment-1 (0.01 Mg ha^{-1} y^{-1}; $P < 0.05$), no-change in Treatment-2 (0.0 Mg ha^{-1} y^{-1}) and a decline in Treatment-3 (–0.09 Mg ha^{-1} y^{-1}; $P < 0.05$). Observed wheat yields do not show any significant decline in Treatment-1 and Treatment-2, but do so in the control (–0.01 Mg ha^{-1} y^{-1}). Simulated wheat yields show no-change in Treatment-1 (0.0 Mg ha^{-1} y^{-1}), and a significant decline in Treatment-2 (0.01 Mg ha^{-1} y^{-1}) and Treatment-3 (–0.06 Mg ha^{-1} y^{-1}). Observed SOC does not show any significant change, whereas the model results show a significant increase in Treatment-1 (0.08 Mg ha^{-1} y^{-1}) and a decline in Treatment-3 (–0.06 Mg ha^{-1} y^{-1}). Total-N also shows no-change in Treatment-1, and a decline in Treatment-2 (–0.008 g kg^{-1} y^{-1}; $P < 0.05$) and Treatment-3 (–0.13 g kg^{-1} y^{-1}; $P < 0.05$). Similar to Pantnagar, model results for Barrackpore show a significant positive correlation between yield and solar radiation in Treatment-1 and Treatment-2, where fertilizers are applied at recommended doses. Under nutrient limitation (Treatment-3), yields are not related to radiation, but to a limiting factor such as total-N (Table 7).

For Nadia, model results show a significant increase in rice yields in Treatment-1 (0.09 Mg ha^{-1} y^{-1}) and a decrease in Treatment-3 (–0.06 Mg ha^{-1} y^{-1}), whereas the observations do not show significant changes. Observed wheat yields, on the other hand, show a significant increase in Treatment-2 (0.07 Mg ha^{-1} y^{-1}), which is reproduced by the model (0.06 Mg ha^{-1} y^{-1}). The increase in wheat yield is well correlated to the increase in solar radiation during this period (Table 6, Table 7). Model results show a decline in SOC in all treatments that is statistically significant in Treatment-2 (–0.17 g kg^{-1} y^{-1}) and Treatment-3 (–0.26 Mg ha^{-1} y^{-1}), whereas in the observations no significant change is found in any of the treatments. Total N does not

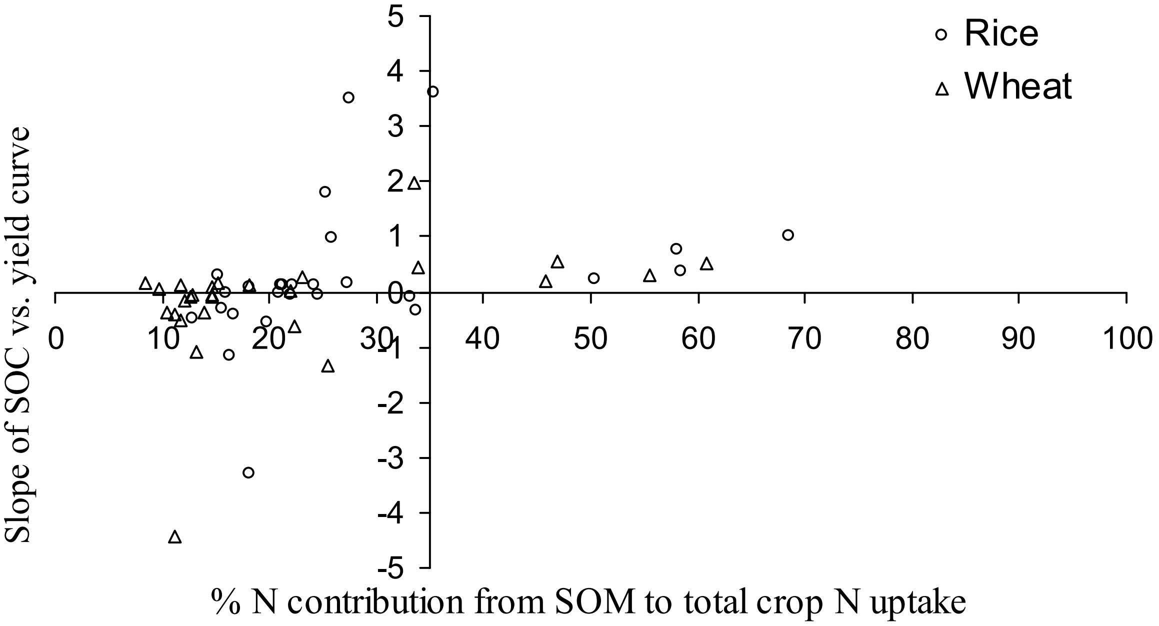


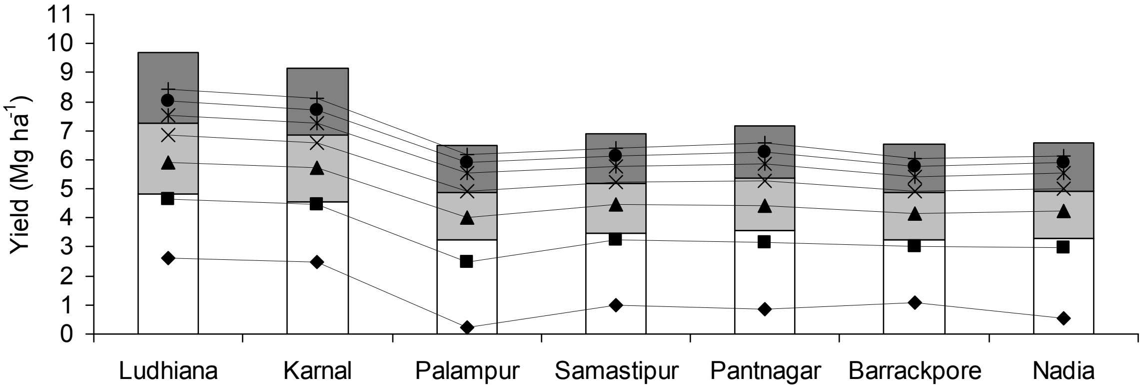
Figure 16. Model results of the relation between nitrogen contribution from SOM as % of total crop N uptake and the slope (change in yield per unit change in SOC) of the SOC vs. yield curve for the different sites and treatments.

show any significant change in any of the treatments, neither in the observations nor in the simulations (Table 5). There is no relation between modeled changes in crop yields in response to changes in SOC (slope of the curve between yield and SOC) for different treatments at various sites when the N supply from SOM is less than 35% of the total N uptake (Figure 16). The response of crop yield to SOC content is linearly related to the fractional contribution of SOM to total crop N-uptake at higher values of the latter. This shows that the importance of SOM in maintaining crop yields is co-determined by the relative contribution of other N sources. The higher the proportion of N-uptake from SOM, the stronger its impact on crop yield.

Nutrient management

The model was applied to estimate the nutrient requirements to realize a target yield at various sites in IGP. Average potential yields (Yp) were calculated for each site, based on incident solar radiation and mean seasonal average daily temperature (see CROP module), calculated as averages for the years of experimentation for the various sites (Table 2). Then, the model was run for rice and wheat with different levels of N (0, 50, 100, 150, 200, 250 and 300 kg ha^{-1}) for 20 years to estimate the fertilizer N requirements to achieve different levels of Yp, assuming no limitations of nutrients

Rice



Wheat

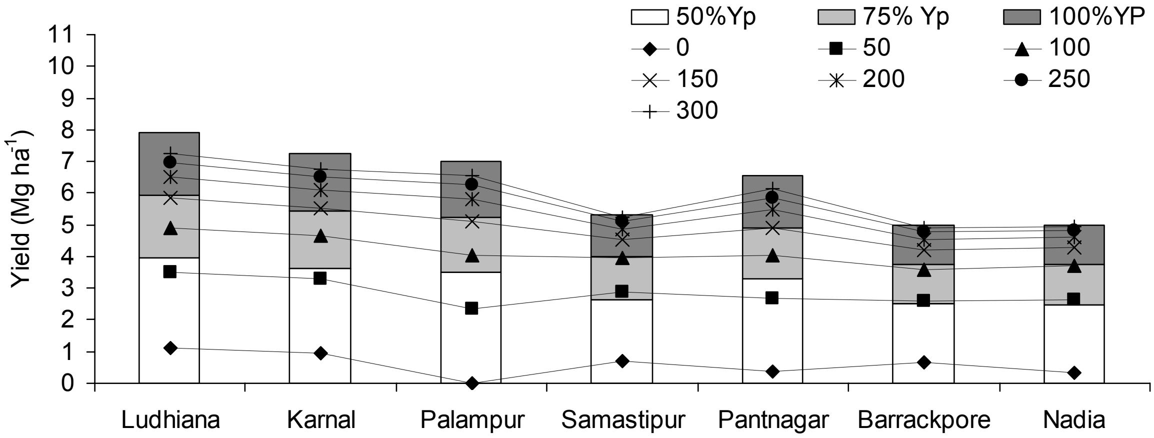


Figure 17. Calculated yields (average of 20 years) for different nitrogen fertilizer doses at various sites of the IGP (assuming no limitations of other nutrients; SOC (g kg^{-1}) initialized for different sites: Ludhiana: 4.0; Karnal: 3.0; Palampur: 14.0; Samastipur: 6.8; Nadia: 8.7; Pantnagar: 8.4; Barrackpore: 4.3).

other than N. The model was re-initialized for SOC in each site by the values at the start of the experimental period and the yield values were averaged for the 20 years.

The model results (Figure 17) show that Yp of rice is higher in Ludhiana (9.7 Mg ha^{-1}) and Karnal (9.1 Mg ha^{-1}) than at the other sites, while Palampur, Barrackpore and Nadia show the lowest Yp (6.5 Mg ha^{-1}). Potential yield for Pantnagar is 16% lower than that for Ludhiana, a value similar (19%) to that reported by Pathak et al. (2003). A yield level of about 50 percent of Yp for rice can be achieved with half the recommended fertilizer N application in Ludhiana, Karnal and Samastipur (Figure 17). For Ludhiana and Karnal with inherently low SOC yields even without any N fertilizer application are relatively high, as a result of significant contributions of NO_3^--N from applied irrigation water. Application of 150 kg N ha^{-1} increases the yield level to almost 75% of Yp for almost all sites, while a further increase affects rice yields only marginally at all sites.

For wheat, similar to rice, Yp (Figure 17) is highest for Ludhiana (7.9 Mg ha^{-1}) and Karnal (7.2 Mg ha^{-1}). For Samastipur (5.3 Mg ha^{-1}), Barrackpore (5.0 Mg ha^{-1}) and Nadia (5.0 Mg ha^{-1}) Yp is lower, because of higher average winter temperatures in these regions. Palampur (7.0 Mg ha^{-1}) and Pantnagar (6.6 Mg ha^{-1}) have a relatively high Yp. With 50 kg N ha^{-1}, 50% Yp can be achieved in Samastipur, Barrackpore and Nadia, where Yp is low. Similar to rice, 75% of Yp in wheat can be realized in Ludhiana, Karnal, Palampur and Pantnagar with 150 kg N ha^{-1}, while in Barrackpore, Samastipur and Nadia the same (75% Yp) can be achieved with about 100 kg N ha^{-1}. These results show that the model may be used for formulation of fertilizer recommendations, to maximize crop yields, economic returns, and to minimize environmental impact due to NO_3^--N pollution.

Resource conservation technologies (RCTs)

Resource conservation technologies (RCTs) are alternatives to puddling and tillage, the most common management practices in rice-based cropping systems of the IGP, and include no-puddling (NP) for rice, reduced or zero tillage (ZT) for wheat and bed planting (BP) for rice and wheat in the rice-wheat system. Limitations and potentials of various RCTs are analyzed with emphasis on SOC and crop yield.

Dry seeded rice (DSR) vs. transplanted rice (TPR)

Puddling is the most common practice in rice, where fields are initially ploughed dry, flooded and then tilled repeatedly (Hobbs, 2001) to create a layer of low permeability. The constraints to wheat production after puddled rice are subsoil compaction, poor drainage, restricted aeration and high mechanical resistance to root growth, resulting in extended periods of land preparation. Such constraints are site-specific and necessitate deep tillage, subsoiling or chiseling to create favorable conditions for wheat in the post-rice soils. An alternative to puddling and transplanting is dry seeding.

Zero-tillage vs. conventional tillage

Changing soil management from conventional tillage (CT) to zero-tillage (ZT) results in increased SOC content (Kern and Johnson, 1993; Paustian et al., 1998). Different zero-tillage practices include surface seeding, zero-till drill, reduced tillage and bed planting.

Surface seeding is the simplest ZT system, where wheat seed is placed on a moist soil surface without any land preparation. The success of surface seeding depends on having optimum moisture at seeding. This system is most suitable for the heavy, poorly drained soils of the eastern IGP. However, it can be adapted to other regions, provided the soil can be kept moist. Zero-till drill uses an inverted T-coulter, attached to a normal seed drill, that makes a narrow groove in the soil for placement of fertilizer and seed in one pass, so that the soil is disturbed only in the groove. Reduced tillage uses a rotavator, while planting in a single pass or by first broadcasting the seeds and incorporating them with the rotavator.

In bed planting systems, crops are grown on raised seed beds. Such ridge and furrow systems have the advantage of better weed control, less lodging and lower water use. It provides opportunities for crop diversification, reduces methane and N_2O emission and groundwater pollution. Planting of rice and wheat on permanent beds allows timely planting of both crops and maintains a favorable soil structure for non-rice crops. The raised bed system allows reduced seed rates, uses less irrigation water, conserves rain water and avoids flooding, facilitates more efficient weed control and fertilizer placement, and minimizes lodging of the wheat crop. It may be especially advantageous where salinity is also a problem.

Based on the two innovative RCTs, four management scenarios were constructed:

1. Transplanted rice - tilled wheat (TPR-TLW)
2. Dry seeded rice - tilled wheat (DSR-TLW)
3. Transplanted rice - zero-tilled wheat (TPR-ZTW)
4. Dry seeded rice - zero-tilled wheat (DSR-ZTW)

The simulations were carried out for 50 years after re-initializing the SOC and nitrogen values (with final values of observed data at the end of experimental period considered) and using long-term average weather characteristics (assuming no climate change) for the various sites. The model is executed with recommended fertilizer-N doses for the various sites (Table 2). The modifications related to the different scenarios are accounted for in the model via a moisture correction factor (M_{fac}) and via an effect of no-tillage (TL_{fac}). The effect of DSR on decomposition of SOC is effectuated a change in water regime from flooded to non-flooded conditions and in terms of soil disturbance from puddled to non-puddled conditions. A change in water regime from flooded to non-flooded saves 30-40% irrigation water (Bhuiyan, 1992; Choudhury et al., 2007). Therefore, the model considers a 30% reduction in the amount of irrigation without any effect of water stress. A reduction in the amount of irrigation water proportionally decreases the N input through irrigation water. Under DSR, nitrogen recovery fraction increases from 35 to 50%, which is typical for an aerobic crop.

Under zero-tillage, the relative decomposition rate of SOC is reduced (see factors influencing SOM decomposition). Residues left in the field after harvest of the crop are removed under the prevailing practice of puddling followed by tillage (TPR-TLW). Therefore, under the TPR-TLW scenario, no crop residues except roots are returned to the soil. However, under DSR and ZTW, a fraction of the residues in the form of straw is returned to the soil after crop harvest. The proportion of straw returned to the soil depends on the method of harvesting. In the north-western parts of the IGP (Ludhiana and Karnal), where combine harvesters are used, about 30% of the straw is returned, whereas in the other parts, where manual harvesting is practiced, it is only 10%.

In the model, we assume that the residues returned are in complete contact with the soil surface and undergo decomposition as explained in the SOM module. The effects of residues on soil temperature and evaporation (through mulching) and on moisture characteristics are not considered in the model.

In Ludhiana, Karnal, Palampur, Pantnagar and Barrackpore SOC increases in all four treatments with a maximum increase in DSR-ZTW, followed by DSR-TLW, TPR-ZTW and TPR-TLW (Table 8). In Nadia, SOC declines in all treatments, whereas in Samastipur all treatments show a decline, except for DSR-ZTW (7.1 g kg^{-1}) where initial SOC is 6.8 g kg^{-1} (Table 8). Higher rates of decomposition of SOC and relatively low yields lead to the decrease in SOC at these two sites.

Residue (straw) addition from wheat increases methane emission under TPR. In Ludhiana and Karnal, where harvesting by a combine harvester is simulated, emissions under the TPR-ZTW scenario are higher than at the other sites.

In general, at all sites, average yields of rice under DSR are higher than under TPR, in both tilled and zero-tilled conditions (Table 8), which is the result of higher N uptake from inorganic N through a higher NRF. However, wheat yields are more or less similar in magnitude. Crop yields of tilled wheat and zero-tilled wheat do not differ much, neither after TPR nor after DSR.

Table 8. Results of scenario analysis under different resource conservation technologies in the Indo-Gangetic Plains of India.

Location Technology	Yield (Mg ha^{-1})		N_{Inorg} (kg ha^{-1})		N_{SOM} (kg ha^{-1})		N_{uptake} (kg ha^{-1})		Methane (kg ha^{-1})		SOC† (g kg^{-1})	Total-N (g kg^{-1})
	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat		
Ludhiana												
TPR+TLW	6.4	5.4	79	82	27	29	106	111	195	0	6.2	0.5
DSR+TLW	7.7	5.4	107	84	32	32	139	115	0	0	7.7	0.5
TPR+ZTW	6.7	5.3	81	84	30	27	112	111	198	0	7.3	0.5
DSR+ZTW	7.9	5.5	107	86	38	32	145	118	0	0	9.3	0.7
Nadia												
TPR+TLW	3.8	3.6	43	63	18	16	61	79	85	0	7.0	0.4
DSR+TLW	4.7	3.6	62	63	22	18	84	81	0	0	7.6	0.5
TPR+ZTW	3.8	3.5	43	63	19	15	62	78	84	0	7.3	0.5
DSR+ZTW	4.7	3.6	62	64	23	18	85	82	0	0	8.2	0.5
Karnal												
TPR+TLW	6.2	5.1	80	81	24	26	104	108	185	0	5.5	0.4
DSR+TLW	7.5	5.2	106	83	30	30	136	113	0	0	6.9	0.5
TPR+ZTW	6.5	5.1	81	84	28	25	109	109	188	0	6.5	0.5
DSR+ZTW	7.6	5.3	106	85	36	31	142	115	0	0	8.5	0.6
Palampur												
TPR+TLW	3.7	3.5	39	49	11	11	50	60	62	0	14.0	1.3
DSR+TLW	4.5	3.6	55	47	11	15	66	62	0	0	18.9	1.6
TPR+ZTW	3.7	3.4	38	49	13	10	51	59	62	0	18.6	1.6
DSR+ZTW	4.5	3.5	54	48	13	12	67	60	0	0	24.5	2.0
Samastipur												
TPR+TLW	4.3	3.9	49	64	23	20	72	84	122	0	5.9	0.5
DSR+TLW	5.4	4.0	71	64	27	23	99	87	0	0	6.6	0.5
TPR+ZTW	4.4	3.9	49	64	24	19	73	83	124	0	6.3	0.5
DSR+ZTW	5.4	4.0	71	65	29	23	100	87	0	0	7.1	0.6
Pantnagar												
TPR+TLW	4.6	4.3	54	69	21	20	74	88	75	0	8.4	0.7
DSR+TLW	5.3	4.7	73	69	20	23	93	93	0	0	9.4	0.7
TPR+ZTW	4.6	4.3	53	68	20	19	74	88	80	0	8.8	0.7
DSR+ZTW	5.6	4.4	76	69	22	22	98	90	0	0	9.9	0.8
Barrackpore												
TPR+TLW	4.4	3.8	49	67	19	17	69	84	91	0	11.1	0.7
DSR+TLW	4.5	4.1	71	71	18	19	89	90	0	0	11.7	0.7
TPR+ZTW	4.1	3.8	49	70	17	17	67	87	103	0	11.4	0.7
DSR+ZTW	4.7	3.9	71	71	19	18	90	89	0	0	12.8	0.8

TPR: Transplanted rice; DSR: Dry seeded rice; TLW: Tilled wheat; ZTW: Zero-tilled wheat; N_{Inorg}: crop uptake from inorganic N sources; N_{SOM}: N uptake from SOM; N_{uptake}: total crop N uptake; SOC: Soil organic carbon.

† Soil organic carbon (g kg^{-1}) initialized for different sites: Ludhiana: 4.0; Karnal: 3.0; Palampur: 14.0; Samastipur: 6.8; Nadia: 8.7; Pantnagar: 8.4; Barrackpore: 4.3. Simulations are carried out with recommended N-fertilizer doses for the various sites.

Discussion

Overall, the summary model described in this paper satisfactorily reproduced observed crop yields, SOC dynamics and total soil N dynamics (Figure 17) for various cropping systems at different sites in the IGP.

The three-pool approach used in this model is a compromise between the minimum number of pools required to adequately represent the variability in rates of decomposition of various soil organic matter components (Craswell and Lefroy, 2001) and the simplification needed in a long-term modeling approach. Initialization of the size and composition of two out of the three pools, on the basis of measured total soil carbon content, involves uncertainty, since their relative sizes are determined by the history of land management, such as cropping pattern, soil and crop management, residue management, etc. Deriving the proportion of labile carbon in the total soil carbon pool from the number of years the soil has been under cultivation (Williams, 1995) is a rather crude approach, as that assumes both a fixed land management and knowledge about the length of the cultivation period. Even though the assumption perse can not be validated independently, it appears the best approach in the current study. More data are needed to further verify its broader-scale applicability.

The simplifications in soil water and nitrogen dynamics introduced in the model are justified by its long-term perspective. Representation of the soil moisture status of flooded rice as saturated and of aerobic crops as at field capacity throughout the growing period, ignores intra-seasonal dynamics. Although within-season alternate wetting and drying in lowland rice systems may have an immense influence on short-term N dynamics (Bouman et al., 2007), its effect on long-term organic carbon dynamics is minor. Since short-term N dynamics are closely associated with those of water in processes such as volatilization, denitrification and leaching, for description of nitrogen availability for the crop, the concept of an exogenously defined recovery fraction (NRF) appears suitable for summarizing these complex processes and their interactions into a single value.

The summary crop module (based on the LUE approach) calculates potential and actual biomass production, LAI, evapotranspiration, total N demand, actual N uptake and N stress. Since the processes involved in biomass production are similar for all crops, coupling this crop growth module to the SOM module provides the flexibility necessary for application of the model to different crops in different cropping systems with minimum crop parameter adaptation.

Although overall performance of the model is satisfactory, deviating results for specific situations could not always be satisfactorily explained. For example, in Barrackpore, the model results show that annual additions of 10 Mg ha^{-1} FYM resulted in an increase in SOC from 7.1 to 8.9 g kg^{-1}, whereas in the 100% NPK treatment it declined to 6.0 g kg^{-1} after 25 years of cropping. In the observations (Saha et al., 2000), addition of FYM (4.5 g kg^{-1}) only had a minor effect in comparison to 100% NPK (4.3 g kg^{-1}). However, recent observations (Manna et al., 2006) of SOC after 30 years of cropping, show an increase in SOC to 7.9, 7.4 and 5.1 (g kg^{-1}) in the 100% NPK+FYM, 100% NPK, and control, respectively.

Discrepancies between observed and simulated crop yields at some of the sites could be due to limitations of specific macro- or micronutrients other than N. For example, in Pantnagar, a decline in rice yield was observed even where SOC was maintained by FYM application, which was attributed to deficiency of Zn (Ram, 2000). Since crop yield is the result of many interacting crop, soil, climate and biotic factors, of which soil organic matter is only one, a decline or an increase in yield could be associated with a change in any of these factors. Therefore, an increase in SOM is not always associated with an increase in yield, as the factor(s) (especially nitrogen availability) improved by an increase in SOM may not be the limiting factor for crop growth. Nitrogen mineralized from soil organic matter contributed 20-80% to total N uptake in the experiments analyzed in this study. The relation between SOM and yield is linear in situations where N contribution from SOM exceeds 35%. A weak correlation between N supply from SOM and crop yield, even in the absence of fertilizer application, is due to substantial quantities of N supplied from alternative sources (irrigation, rainfall, etc.) at some of the sites.

Crop yield trends over time and the relationship between SOM and crop productivity at various sites of the IGP show varying trends for both observed and simulated values. Of the three sites in Ludhiana, a significant decline in yield was observed only in Ludhiana-3, explained by Bhandari et al. (2002) by a decline in total soil-N. Total soil-N indeed decreased significantly over time at this site, in both the observations and the simulations for the 100% NPK (observed (–0.004 g kg^{-1} y^{-1}) vs. simulated (–0.005 g kg^{-1} y^{-1})) and the control (observed (–0.004 g kg^{-1} y^{-1}) vs. simulated (–0.008 g kg^{-1} y^{-1})) treatments (Table 5). Bhandari et al. (2002) reported the rate of decline as –0.03 g kg^{-1} y^{-1}, however, without considering the initial 5 years. Nevertheless, none of the factors tested, such as solar radiation, SOC and total soil nitrogen appeared significantly correlated to yield (Table 7). The model results in general show a significant decline in all those treatments at the various sites, where no fertilizers or manures are added (Treatments-3; Table 5). The decline in yield in the treatments without fertilizer or manure application is associated with a decrease in SOC, showing a direct link between crop yield and SOC. However, observations did not show such a strong relation between yield and SOC, except for Pantnagar. For the observations with a recommended NPK application, a significant decrease in yield was found in Ludhiana-3, Pantnagar and Barrackpore (Table 5), but it was positively correlated to SOC only for Pantnagar and Barrackpore (Table 7). The model also reproduced this decline in yield at these sites, except for Barrackpore. For Pantnagar, a decline in yield is observed even when SOC was maintained with FYM application. This leads to the conclusion that under long-term intensive cultivation, many macro (NPK) and/or micro (Zn, Fe, Mn, etc.) nutrients essential for plant growth may become depleted, even with a balanced NPK fertilizer application, resulting in declining productivity.

The current average annual yield (rice + wheat) of the sites considered in the current study is small (6-12 Mg ha^{-1}, Table 4) compared to their potentials (Yp, 12-18 Mg ha^{-1}; Figure 17). Aggarwal et al. (2000) also reported potential (rice + wheat) system productivities in the range of 12-19 Mg ha^{-1} for the IGP of India. One of the major reasons for the yield gap is that present recommendations for NPK for rice and wheat at many sites is inadequate (Regmi et al., 2002). Estimation of optimum N-doses is therefore important to bridge the yield gap and to reverse the trend of decline. The model application for estimating N-fertilizer requirements to achieve different yield levels at different sites of the IGP shows that about 75% of Yp for rice can be realized with 150 kg N ha^{-1} at most of the sites (Figure 17). For wheat, this varies: for Samastipur, Nadia and Barrackpore 75 % of Yp can be achieved with 100 kg N ha^{-1}, whereas for other sites such as Ludhiana, Karnal and Pantnagar, 150 kg N ha^{-1} is needed. This analysis allows identification of the reasons for the higher productivity in soils low in organic carbon such as in Ludhiana, in comparison to soils with a higher organic carbon content (e.g. Pantnagar). The higher yield potential in Ludhiana (Figure 17) associated with a higher incident solar radiation (Figure 2) is one of the reasons. Long-term average potential biomass yield for rice in Ludhiana is about 10 Mg ha^{-1} compared to 7.2 Mg ha^{-1} in Pantnagar, and for wheat at the two sites it amounts to 8 and 6.6 Mg ha^{-1}, respectively. A higher (18%) system productivity (rice +wheat) in terms of grain yield for Ludhiana compared to Pantnagar has also been reported by Pathak et al. (2003). In Ludhiana, irrigation water is a major source of nitrogen that contributes on average 30 and 8 kg ha^{-1}, respectively, to nitrogen uptake for rice and wheat.

Since crops like rice and wheat remove substantial quantities of major nutrients as compared to the rate at which they are added externally through fertilizers, a negative nutrient balance for N (Ram, 2000; Bhandari et al., 2002), P (Yadvinder et al., 2000), or K (Regmi et al., 2002) is not a surprise in the long run. Micro-nutrient deficiencies (Yadav et al., 1998) also add to this problem. Therefore, a carefully balanced nutrient management is necessary to sustain a high crop yield. This needs a careful analysis of reasons for yield limitation. Recycling of crop residues, which are otherwise removed or burned at present, can improve the soil environment into a sustainable production system (Narang and Virmani, 2001; Samra et al., 2003). Crop residues, when incorporated, become an important source of carbon and nutrients (including micro-nutrients) to soil, enhancing microbial activity and soil aggregation (Beri et al., 1992; Patra et al., 1992; Verma and Bhagat, 1992; Meelu et al., 1994; Beri et al., 1995; Sidhu et al., 1995; Walia et al., 1995; Yadvinder et al., 2000). However, crop residue incorporation may also increase the methane emission under the current (flooded rice) management practices. The model results show a higher rate of methane emission with increase in rate of addition of organic amendments (GM, FYM, straw, etc.) in continuously flooded rice. Incorporation of GM and FYM to wheat instead of rice may be an alternative strategy. However, wheat residues still have to be removed or burned. Therefore, the present rice-based cropping system demands alternative crop and soil management practices for efficient utilization of its resources in a sustainable way. Resource conservation technologies like DSR and ZTW are some alternative choices. The model results show that DSR and ZTW result in higher crop yields, SOC and total-N, and lower methane emissions. These technologies are more water productive and energy saving and can address the problems related to receding groundwater tables, destroying soil structure and reducing GHGs emissions under rice-based cropping systems.

Concluding remarks

Rice-based cropping systems are complex production systems in terms of their different environmental conditions needed for the different crops. The model could adequately represent this system and the relation between SOM and crop yield by using the general principles of plant production and its simplification through a summary model. The role of SOM in crop production is not only through its nutrient-supplying function, but also through its effect on soil structure that improves water holding capacity, soil aeration, water and nutrient movement in the soil. However, in the present study the model only considers the nitrogen-supplying function of SOM. The model satisfactorily reproduced observed results of yield, SOC, and total-N for different treatments under various sites. The model results show that SOM is not always a direct measure of a soil's nitrogen supplying capacity and the importance of SOM as a nutrient source for crops is relative to other N sources. On average, N contribution from SOM to crop growth is found as low as 20% in fertilized treatments to as high as 80% in some unfertilized treatments. If SOM holds a major share of total crop N-uptake, crop yield may be more sensitive to SOC changes. The model results show that when N contribution to crop uptake from SOM is greater than 35%, changes in SOC may affect the crop yield in a long run.

References

Adams, T.M. and Adams, S.N., 1983. The effects of liming and soil pH on carbon and nitrogen contained in the soil biomass. Journal of Agricultural Science 101, 553-558.

Addiscott, T.M., 1983. Kinetics and temperature relationships of mineralization and nitrification in Rothamsted soils with differing histories. Journal of Soil Science 34, 343-353.

Aggarwal, P.K., Talukdar, K.K. and Mall, R.K., 2000. Potential yields of rice-wheat system in the Indo-Gangetic Plains of India. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India and Indian Agricultural Research Institute, New Delhi, India, 16 pp.

Amato, M. and Ladd, J.N., 1992. Decomposition of ^{14}C-labelled glucose and legume material in soils: properties influencing the accumulation of organic residue C and microbial biomass C. Soil Biology and Biochemistry 24, 455-464.

Amelung, W. and Zech, W., 1996. Organic species in ped surface and core fractions along a climosequence in the prairie, North America. Geoderma 74, 193-206.

Anonymous, 1997. Organic Resources Database. Tropical Soil Biology and Fertility Institute, Nairobi, Kenya and Wye College, University of London.

Bameix, A.J., Arnozis, P.A. and Guitman, M.R., 1992. The regulation of nitrogen accumulation in the grain of wheat plants (*Triticum aestivum*). Physiologia Plantarum 86, 609-615.

Beri, V., Sidhu, B.S., Bhat, A.K. and Singh, B.P., 1992. Nutrient balance and soil properties as affected by management of crop residues. In: Nutrient management for sustained productivity. Proceedings of International Symposium, Department of Soils, Punjab Agricultural University, Ludhiana.

Beri, V., Sidhu, B.S., Bahl, G.S. and Bhat, A.K., 1995. Nitrogen and phosphorus transformations as affected by crop residue management-practices and their Influence on crop yield. Soil Use and Management 11, 51-54.

Bhandari, A.L., Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D. and Gupta, R.K., 2002. Yield and soil nutrient changes in a long-term rice-wheat rotation in India. Soil Science Society of America Journal 66, 162-170.

Bhuiyan, S.I., 1992. Water management in relation to crop production: case study on rice. Outlook on Agriculture 21, 293-299.

Biswas, B., Ghosh, D.C., Dasgupta, M.K., Trivedi, N., Timsina, J. and Dobermann, A., 2006. Integrated assessment of cropping systems in the Eastern Indo-Gangetic plain. Field Crops Research 99, 35-47.

Bock, M.J. and Mayer, L.M., 2000. Mesodensity organo-clay associations in a near-shore sediment. Marine Geology 163, 65-75.

Bouman, B.A.M. and Van Laar, H.H., 2006. Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions. Agricultural Systems 87, 249-273.

Bouman, B.A.M., Humphreys, E., Tuong, T.P. and Barker, R., 2007. Rice and Water. Advances in Agronomy 92, 187-237.

Bunnell, F.L., Tait, D.E.N., Flanagan, P.W. and Van Clever, K., 1977. Microbial respiration and substrate weight loss-I: A general model of the influences of abiotic variables. Soil Biology and Biochemistry 9, 33-40.

Carter, M.R., 1986. Microbial biomass and mineralizable nitrogen in solonetzic soils: influence of gypsum and lime amendments. Soil Biology and Biochemistry 18, 531-537.

Carter, M.R., Angers, D.A., Gregorich, E.G. and Bolinder, M.A., 1997. Organic carbon and nitrogen stocks and storage profiles in cool, humid soils of eastern Canada. Canadian Journal of Soil Science 77, 205-210.

Cassman, K.G., Peng, S., Olk, D.C., Ladha, J.K., Reichardt, W., Dobermann, A. and Singh, U., 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. Field Crops Research 56, 7-39.

Chander, K., Goyal, S. and Kapoor, K.K., 1994. Effect of sodic water irrigation and farmyard manure application on soil microbial biomass and microbial activity. Applied Soil Ecology 1, 139-144.

Chaudhary, T.N., 1997. Water management in rice for efficient production. Directorate of Water Management Research, Patna, India.

Choudhury, B.J., 2001. Modeling radiation- and carbon-use efficiencies of maize, sorghum, and rice. Agricultural and Forest Meteorology 106, 317-330.

Choudhury, B.U., Bouman, B.A.M. and Singh, A.K., 2007. Yield and water productivity of rice-wheat on raised beds at New Delhi, India. Field Crops Research 100, 229-239.

Craswell, E.T. and Lefroy, R.D.B., 2001. The role and function of organic matter in tropical soils. Nutrient Cycling in Agroecosystems 61, 7-18.

Cregan, P.B. and Vanberkum, P., 1984. Genetics of nitrogen metabolism and physiological and biochemical selection for increased grain crop productivity. Theoretical and Applied Genetics 67, 97-111.

Dawe, D., Dobermann, A., Moya, P., Abdulrachman, S., Singh, B., Lal, P., Li, S.Y., Lin, B., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., Tan, P.S. and Zhen, Q.X., 2000. How widespread are yield declines in long-term rice experiments in Asia? Field Crops Research 66, 175-193.

De Wit, C.T. and Penning de Vries, F.W.T., 1982. L'analyse des systèmes de production primaire. In: Penning de Vries, F. W. T. and Djitèye, M. A., (Eds.) La productivité des pâturages sahéliens. Une étude des sols, des végétations et de l'exploitation de cette resource naturelle. Agricultural Research Reports 918, Pudoc, Wageningen.

Donatelli, M., Bellocchi, G. and Fontana, F., 2003. RadEst3.00: Software to estimate daily radiation data from commonly available meteorological variables. European Journal of Agronomy 18, 363-367.

el-Shakweer, M.H.A., Gomah, A.M., Barakat, M.A. and Abdel-Ghaffar, A.S., 1977. Effects of salts on decomposition of plant residues. In: Proceedings of a Symposium on Soil Organic Matter Studies I, Braunschweig (Germany, F.R.), 6 Sep 1976. FAO and International Atomic Energy Agency, Vienna, Austria, pp. 205-213.

Ellert, B.H. and Bettany, J.R., 1992. Temperature dependence of net nitrogen and sulfur mineralization. Soil Science Society of America Journal 56, 1133-1141.

Eswaran, H., Vandenberg, E. and Reich, P., 1993. Organic carbon in soils of the world. Soil Science Society of America Journal 57, 192-194.

Gallagher, J.N. and Biscoe, P.V., 1978. Radiation absorption, growth and yield of cereals. Journal of Agricultural Science 91, 47-60.

Garnier, P., Neel, C., Aita, C., Recous, S., Lafolie, F. and Mary, B., 2003. Modelling carbon and nitrogen dynamics in a bare soil with and without straw incorporation. European Journal of Soil Science 54, 555-568.

Giller, K.E. and Merckx, R., 2003. Exploring the boundaries of N_2-fixation in cereals and grasses: a hypothetical and experimental framework. Symbiosis 35, 3-17.

Goncalves, J.L.M. and Carlyle, J.C., 1994. Modelling the influence of moisture and temperature on net nitrogen mineralization in a forested sandy soil. Soil Biology and Biochemistry 26, 1557-1564.

Grant, R.F. and Rochette, P., 1994. Soil microbial respiration at different water potentials and temperatures: theory and mathematical modeling. Soil Science Society of America Journal 58, 1681-1690.

Groenendijk, P. and Kroes, J.G., 1999. Modelling the nitrogen and phosphorus leaching to groundwater and surface water, Report No.144, DLO Winand Staring Centre, Wageningen, 138 pp.

Gupta, R.K., Naresh, R.K., Hobbs, P.R. and Ladha, J.K., 2002. Adopting conservation agriculture in rice-wheat systems of the Indo-Gangetic Plains - new opportunities for saving water. In: Bouman, B. A. M., Hengsdijk, H., Hardy, B., Bindraban, P. S., Tuong, T. P. and Ladha, J. K., (Eds.) Water-wise rice production. International Rice Research Institute, Los Banõs, Philippines, pp. 207-222.

Hassink, J., 1995. Organic matter dynamics and N mineralization in grassland soils. PhD thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Hassink, J., 1996. Preservation of plant residues in soils differing in unsaturated protective capacity. Soil Science Society of America Journal 60, 487-491.

Hassink, J., Whitmore, A.P. and Kubat, J., 1997. Size and density fractionation of soil organic matter and the physical capacity of soils to protect organic matter. European Journal of Agronomy 7, 189-199.

Hobbs, P.R., 2001. Tillage and crop establishment in South Asian rice-wheat systems: present practices and future options. Journal of Crop Production 4, 1-22.

Hobbs, P.R., Singh, Y., Giri, G.S., Lauren, J.G. and Duxbury, J.M., 2002. Direct-seeding and reduced-tillage options in the rice-wheat systems of the Indo-Gangetic Plains of South Asia. In: Pandey, S., Mortimer, M., Wade, L., Tuong, T. P., Lopez, K. and Hardy, B., (Eds.) Direct seeding: research issues and opportunities. International Rice Research Institute (IRRI), Manila, Philippines, pp. 201-215.

Huang, Y., Sass, R.L. and Fisher, Jr., F.M., 1998. A semi-empirical model of methane emission from flooded rice paddy soils. Global Change Biology 4, 247-268.

Huang, Y., Zhang, W., Zheng, X.H., Li, J. and Yu, Y.Q., 2004. Modeling methane emission from rice paddies with various agricultural practices. Journal of Geophysical Research 109, 1-12.

Huang, Y.A.O., Sass, R. and Fisher, F., 1997a. Methane emission from Texas rice paddy soils. 1. Quantitative multi-year dependence of CH_4 emission on soil, cultivar and grain yield. Global Change Biology 3, 479-489.

Huang, Y.A.O., Sass, R. and Fisher, F., 1997b. Methane emission from Texas rice paddy soils. 2. Seasonal contribution of rice biomass production to CH_4 emission. Global Change Biology 3, 491-500.

Jamieson, P.D. and Semenov, M.A., 2000. Modelling nitrogen uptake and redistribution in wheat. Field Crops Research 68, 21-29.

Jamieson, P.D., Semenov, M.A., Brooking, I.R. and Francis, G.S., 1998. Sirius: a mechanistic model of wheat response to environmental variation. European Journal of Agronomy 8, 161-179.

Jandle, R. and Sollins, P., 1997. Water-extractable soil carbon in relation to the below ground carbon cycle. Biology and Fertility of Soils 25, 196-201.

Johnson, M.G., Levine, E.R. and Kern, J.S., 1995. Soil organic matter: distribution, genesis, and management to reduce greenhouse gas emission. Water, Air, and Soil Pollution 82, 593-615.

Kern, J.S. and Johnson, M.G., 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Science Society of America Journal 57, 200-210.

Kilbertus, G., 1980. Etude des microhabitats contenus dans les agrégats du sol. Leur relation avec la biomasse bactérienne et la taille des procaryotes présents. Revue d'Ecologie et de Biologie du Sol 17, 543-557.

Kiniry, J.R., McCauley, G., Xie, Y. and Arnold, J.G., 2001. Rice parameters describing crop performance of four U.S. cultivars. Agronomy Journal 93, 1354-1361.

Kiniry, J.R., Jones, C.A., O'Toole, J.C., Blanchet, R., Cabelguenne, M. and Spanel, D.A., 1989. Radiation-use efficiency in biomass accumulation prior to grain-filling for five grain-crop species. Field Crops Research 20, 51-64.

Kirschbaum, M.U.F., 1995. The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biology and Biochemistry 27, 753-760.

Kononova, M.M., 1975. Humus of virgin and cultivated soils. In: Gieseking, J. E., (Ed.) Soil components, Vol. 1. Springer, New York, pp. 475-526.

Krull, E.S., Baldock, J.A. and Skjemstad, J.O., 2003. Importance of mechanisms and processes of the stabilisation of soil organic matter for modelling carbon turnover. Functional Plant Biology 30, 207-222.

Kundu, A.L. and Samui, R.C., 2000. Long-term soil fertility experiment in rice-wheat cropping system in West Bengal. Rice-Wheat Consortium Paper Series 6, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India 63-67 pp.

Ladd, J.N., Oades, J.M. and Amato, M., 1981. Microbial biomass formed from ^{14}C, ^{15}N-labelled plant material decomposing in soils in the field. Soil Biology and Biochemistry 13, 119-126.

Ladd, J.N., Amato, M. and Oades, J.M., 1985. Decomposition of plant material in Australian soils. III. Residual organic and microbial biomass C and N from isotope-labelled legume material and soil organic matter, decomposing under field conditions. Australian Journal of Soil Research 23, 603-611.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K. and Hobbs, P.R., 2003. How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crops Research 81, 159-180.

Laura, R.D., 1973. Effects of sodium carbonate on carbon and nitrogen mineralisation of organic matter added to soil. Geoderma 9, 15-26.

Leiros, M.C., Trasar-Cepeda, C., Seoane, S. and Gil-Sotres, F., 1999. Dependence of mineralization of soil orgnic matter on temperature and moisture. Soil Biology and Biochemistry 31, 327-335.

Li, C., Frolking, S. and Harriss, R., 1994. Modeling carbon biogeochemistry in agricultural soils. Global Biogeochemical Cycles 8, 237-254.

Linn, D.M. and Doran, J.W., 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non-tilled soils. Soil Science Society of America Journal 48, 1267-1272.

Lloyd, J. and Taylor, J.A., 1994. On the temperature dependence of soil respiration. Functional Ecology 8, 315-323.

Makkink, G.F., 1957. Testing the Penman formula by means of lysimeters. Journal of the Institute of Water Engineers 11, 277-288.

Mandal, B.C., Roy, A.B., Saha, M.N. and Mandal, A.K., 1984. Wheat yield and soil nutrient status as influenced by continuous cropping and manuring in a jute-rice-wheat rotation. Journal of the Indian Society of Soil Science 32, 697-700.

Manna, M.C., Swarup, A., Wanjari, R.H., Singh, Y.V., Ghosh, P.K., Singh, K.N., Tripathi, A.K. and Saha, M.N., 2006. Soil organic matter in a West Bengal Inceptisol after 30 years of multiple cropping and fertilization. Soil Science Society of America Journal 70, 121-129.

Meelu, O.P., Singh, Y., Singh, B., Khera, T.S. and Kumar, K., 1994. Recycling of crop residues and green manuring for soil and crop productivity improvement in rice-wheat cropping system. In: Humphreys, E., Murray, E. A., Clampett, W. S. and Lewin, L. Q., (Eds.) Temperate rice: achievements and potential, Vol. 2. NSW Agriculture, Griffith, NSW, Australia, pp. 605-613.

Monteith, J.L., 1977. Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 281, 277-294.

Monteith, J.L., 1990. Conservative behaviour in the response of crops to water and light. In: Rabbinge, R., Goudriaan, J., Van Keulen, H., Penning de Vries, F. W. T. and Van Laar, H. H., (Eds.) Theoretical production ecology: reflections and prospects. Pudoc, Wageningen, pp. 3-16.

Motavalli, P.P., Palm, C.A., Parton, W.J., Elliott, E.T. and Frey, S.D., 1995. Soil pH and organic C dynamics in tropical forest soils: evidence from laboratory and simulation studies. Soil Biology and Biochemistry 27, 1589-1599.

Muchow, R.C., 1985. An analysis of the effects of water deficits on grain legumes grown in a semi-arid tropical environment in terms of radiation interception and its efficiency of use. Field Crops Research 11, 309-323.

Muchow, R.C., Robertson, M.J. and Pengelly, B.C., 1993. Radiation use efficiency of soybean, mungbean and cowpea under different environmental conditions. Field Crops Research 32, 1-16.

Narang, R.S. and Virmani, S.M., 2001. Rice-wheat cropping systems of the Indo-Gangetic Plains of India. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, and International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradesh, India, 36 pp.

Nelson, P.N., Ladd, J.N. and Oades, J.M., 1996. Decomposition of ^{14}C-labelled plant material in a salt-affected soil. Soil Biology and Biochemistry 28, 433-441.

Oades, J.M., 1988. The retention of organic matter in soils. Biogeochemistry 5, 35-70.

Olk, D.C., Brunetti, G. and Senesi, N., 2000. Decrease in humification of organic matter with intensified lowland rice cropping: a wet chemical and spectroscopic investigation. Soil Science Society of America Journal 64, 1337-1347.

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal 51, 1173-1179.

Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S.K., Mishra, B., Sastri, A.S.R.A.S., Aggarwal, H.P., Das, D.K. and Gupta, R.K., 2003. Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. Field Crops Research 80, 223-234.

Patra, D.D., Bhandari, S.C. and Misra, A., 1992. Effect of plant residues on the size of microbial biomass and nitrogen mineralization in soil: incorparation of cowpea and wheat straw Soil Science and Plant Nutrition 38, 1-6.

Paustian, K., Elliott, E.T. and Carter, M.R., 1998. Tillage and crop management impacts on soil C storage: Use of long-term experimental data. Soil Tillage Research 47, 1-5.

Penning de Vries, F.W.T., Jansen, D.M., Ten Berge, H.F.M. and Bakema, A., 1989. Simulation of ecophysiological processes of growth in several annual crops. Centre for Agricultural Publishing and Documentation, Wageningen, 308 pp.

Post, W.M., 1990. Carbon Sinks - Reply. American Scientist 78, 397.

Prasad, B. and Sinha, S.K., 2000. Long-term effects of fertilizers and organic manures on crop yields, nutrient balance, and soil properties in rice-wheat cropping system in Bihar. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K., (Eds.) Long-term soil fertility experiments with rice-wheat rotations in South Asia. Rice-Wheat Consortium Paper Series 6. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 105-119.

Priestley, C.H.B. and Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Review 100, 81-91.

Qi, Y. and Xu, M., 2001. Separating the effects of moisture and temperature on soil CO_2 efflux in a coniferous forest in the Sierra Nevada mountains. Plant and Soil 237, 15-23.

Ram, N., 1998. Effect of continuous fertilizer use on soil fertility and productivity of a Mollisol. In: Swarup, A., Damodar, R. D. and Prasad, R. N., (Eds.) Long-term soil fertility management through integrated plant nutrient supply. All India Coordinated Research Project (AICRP) on long-term fertilizer experiments. Indian Institute of Soil Science, Bhopal, India pp. 229-237.

Ram, N., 2000. Long-term effects of fertilizers on rice-wheat-cowpea productivity and soil properties in Mollisols. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K., (Eds.) Long-term soil fertility experiments with rice-wheat rotations in South Asia. Rice-Wheat Consortium Paper Series 6 Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 50-55.

Ransom, B., Kim, D., Kastner, M. and Wainwright, S., 1998. Organic matter preservation on continental slopes: Importance of mineralogy and surface area. Geochimica et Cosmochimica Acta 62, 1329-1345.

Reeves, D.W., 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil and Tillage Research 43, 131-167.

Regmi, A.P., Ladha, J.K., Pathak, H., Pasuquin, E., Bueno, C., Dawe, D., Hobbs, P.R., Joshy, D., Maskey, S.L. and Pandey, S.P., 2002. Yield and soil fertility trends in a 20-year rice-rice-wheat experiment in Nepal. Soil Science Society of America Journal 66, 857-867.

Rodrigo, A., Recous, S., Neel, C. and Mary, B., 1997. Modelling temperature and moisture effects on C-N transformations in soils: comparison of nine models. Ecological Modelling 102, 325-339.

Ross, D.J. and Cairns, A., 1978. Influence of temperature on biochemical processes in some soils from tussock grasslands. 1. Respiratory activity. New Zealand Journal of Science 21, 581-589.

Saggar, S., Parshotam, A., Sparling, G.P., Feltham, C.W. and Hart, P.B.S., 1996. C-14 labelled ryegrass turnover and residence times in soils varying in clay content and mineralogy. Soil Biology and Biochemistry 28, 1677-1686.

Saha, M.N., Chaudhury, J., Saha, A.R. and Ray, P.K., 1998. Effect of intensive cropping and fertilizer use on soil properties and crop yields in a long-term experiment. In: Swarup, A., Reddy, D. D. and Prasad, R. N., (Eds.) Long-term soil fertility management through integrated plant nutrient supply. Indian Institute of Soil Science, Bhopal, India, pp. 215-220.

Saha, M.N., Saha, A.R., Mandal, B.C. and Ray, P.K., 2000. Effects of long-term jute-rice-wheat cropping system on crop yields and soil fertility In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K., (Eds.) Long-term soil fertility experiments with rice-wheat rotations in South Asia. Rice-Wheat Consortium Paper Series 6. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 94-104.

Samra, J.S., Bijay-Singh and Kumar, K., 2003. Managing Crop Residues in the Rice-Wheat System of the Indo-Gangetic Plain. In: Ladha, J. K., Hill, E., Duxbury, J. M., Gupta, R. K. and Buresh, R. J., (Eds.) Improving the productivity and sustainability of rice-wheat systems: Issues and impact. ASA Special Publication. 65. American Society of Agronomy, Madison, Wisconsin pp. 173-195.

Samui, R.C., Kundu, A.L., Mazumdar, D. and Mani, P.K., 1998. Integrated nutrient management in rice-wheat system in West-Bengal. In: Swarup, A., Reddy, D. D. and Prasad, R. N., (Eds.) Long-term soil fertility management through integrated plant nutrient supply. Indian Institute of Soil Science, Bhopal, India, pp. 256-259.

Sanchez, P.A. and Logan, T.J., 1992. Myths and science about the chemistry and fertility of soils in the tropics. In: Lal, R. and Sanchez, P. A., (Eds.) Myths and science of soil of the tropics. SSSA Special Publication 29, Soil Science Society of America, Madison, WI, pp. 35-46.

Schjønning, P., Thomsen, I.K., Møberg, J.P., de Jonge, H., Kristensen, K. and Christensen, B.T., 1999. Turnover of organic matter in differently textured soils: I. Physical characteristics of structurally disturbed and intact soils. Geoderma 89, 177-198.

Schleser, G.H., 1982. The response of CO_2 evolution from soils to global temperature changes. Zeitschrift für Naturforschung 37, 287-291.

Seligman, N.G. and Van Keulen, H., 1981. PAPRAN: a simulation model of annual pasture production limited by rainfall and nitrogen. In: Frissel, M. J. and van Veen, J. A., (Eds.) Simulation of nitrogen behavior of soil plant systems. Pudoc, Wageningen, pp. 192-220.

Sharma, P.K., Ladha, J.K., Verma, T.S., Bhagat, R.M. and Padre, A.T., 2003. Rice-wheat productivity and nutrient status in a lantana- (Lantana spp.) amended soil. Biology and Fertility of Soils 37, 108-114.

Shibu, M.E., Leffelaar, P.A., Van Keulen, H. and Aggarwal, P.K., 2006. Quantitative description of soil organic matter dynamics-A review of approaches with reference to rice-based cropping systems. Geoderma 137, 1-18.

Sidhu, B.S., Beri, V. and Gosal, S.R., 1995. Soil microbial health as affected by crop residue management. In: Proceedings of the national symposium on developments in soil science, Ludhiana, India 2-5 November, 1995. Indian Society of Soil Science, New Delhi, India.

Sierra, J., 1997. Temperature and soil moisture dependence of N mineralization in intact soil cores. Soil Biology and Biochemistry 29, 1557-1563.

Sinclair, T.R. and Muchow, R.C., 1999. Radiation use efficiency. Advances in Agronomy 65, 215-265.

Thomsen, I.K., Schjønning, P., Jensen, B., Kristensen, K. and Christensen, B.T., 1999. Turnover of organic matter in differently textured soils. II. Microbial activity as influenced by soil water regimes. Geoderma 89, 199-218.

Timsina, J. and Connor, D.J., 2001. Productivity and management of rice-wheat cropping systems: issues and challenges. Field Crops Research 69, 93-132.

Tripathi, R.P., 1996. Water management in rice-wheat system. In: Pandey, R. K., Dwivedi, B. S. and Sharma, A. K., (Eds.) Rice-Wheat Cropping System. Project Directorate for Cropping Systems Research, Modipuram, India, pp. 134-147.

Van Keulen, H., 1995. Sustainability and long-term dynamics of soil organic matter and nutrients under alternative management strategies. In: Bouma, J., Kuyvenhoven, A., Bouman, B. A. M., Luyten, J. C. and Zandstra, H. G., (Eds.) Eco-regional approaches for sustainable land use and food production. Kluwer Academic Publishers, Dordrecht, pp. 353-375.

Van Keulen, H. and Wolf, J., 1986. Modeling of agricultural production: weather, soils, and crops. Pudoc, Wageningen, 479 pp.

Van Keulen, H. and Seligman, N.G. 1987. Simulation of water use, nitrogen nutrition and growth of a spring wheat crop Pudoc, Wageningen, The Netherlands, 308 pp.

Verberne, E.L.J., Hassink, J., De Willigen, P., Groot, J.J.R. and van Veen, J.A., 1990. Modelling organic matter dynamics in different soils. Netherlands Journal of Agricultural Sciences 38, 221-238.

Verma, T.S. and Bhagat, R.M., 1992. Impact of rice straw management practices on yield, nitrogen uptake and soil properties in a wheat-rice rotation in northern India. Fertilizer Research 33, 97-106.

Walia, S.S., Brar, S.S. and Kler, D.S., 1995. Effect of management of crop residues on soil properties in rice-wheat cropping system. Environmental Ecololgy 13, 503-507.

Wang, Z.P., Lindau, C.W., De Laune, R.D., Patrick Jr., W.H., 1993. Methane emission and entrapment in flooded rice soils as affected by soil properties. Biology and Fertiliy of Soils 16, 163-168.

West, T.O. and Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Science Society of America Journal 66, 1930-1946

White, J.W. and Rodriguez-Aguilar, A., 2001. An agroclimatological characterization of the Indo-Gangetic Plains. Journal of Crop Production 3, 53-65.

Williams, J.R., 1995. The EPIC model. In: Singh, V. P., (Ed.) Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, CO, pp. 909-1000.

Wong, V.N.L., Greene, R.S.B., Murphy, B.W., Dalal, R. and Mann, S., 2004. Carbon dynamics in salt-affected soils In: Roach, I.C (Ed.) Proceedings of the CRC LEME Regional Regolith Symposia, University of Adelaide, Australia. CRC LEME, pp. 407-410.

Yadav, R.L., Yadav, D.S., Singh, R.M. and Kumar, A., 1998. Long term effects of inorganic fertilizer inputs on crop productivity in a rice-wheat cropping system. Nutrient Cycling in Agroecosystems 51, 193-200.

Yaduvanshi, N.P.S., 2001. Effect of five years of rice-wheat cropping and NPK fertilizer use with and without organic and green manures on soil properties and crop yields in a reclaimed sodic soil. Journal of Indian Society of Soil Science 49, 714-719.

Yadvinder, S., Singh, B., Meelu, O.P. and Khind, C.S., 2000. Long-term effects of organic manuring and crop residues on the productivity and sustainability of rice-wheat cropping system in Northwest India. In: Abrol, I. P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K., (Eds.) Long-term soil fertility experiments in rice-wheat cropping systems, Rice-Wheat Consortium Paper Series 6. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 149-62.

Yadvinder, S., Bijay, S., Meelu, O.P. and Khind, C.S., 2000 Long-term effects of organic manuring and crop residues on the productivity and sustainability of rice-wheat cropping system in Northwest India. In: Swarup, A., Reddy, D. D. and Prasad, R. N., (Eds.) Long-term soil fertility management through integrated plant nutrient supply. Indian Institute of Soil Science, Bhopal, India, pp. 149-162

Yadvinder, S., Bijay, S., Ladha, J.K., Khind, C.S., Khera, T.S. and Bueno, C.S., 2004b. Effects of residue decomposition on productivity and soil fertility in rice-wheat rotation. Soil Science Society of America Journal 68, 854-864.

Yadvinder, S., Bijay, S., Ladha, J.K., Khind, C.S., Gupta, R.K., Meelu, O.P. and Pasuquin, E., 2004a. Long-term effects of organic inputs on yield and soil fertility in the rice-wheat rotation. Soil Science Society of America Journal 68, 845-853.

Zunino, H., Borie, F., Aguilera, S., Martin, J.P. and Haider, K., 1982. Decomposition of 14C-labeled glucose, plant and microbial products and phenols in volcanic ash-derived soils of Chile. Soil Biology and Biochemistry 14, 37-43.

Appendix

Parameters used in the summary model for long-term dynamics of C and N.

Parameters	*Value*
Soil organic matter	
Maximum relative rate of decomposition of labile pool, y^{-1}	0.15
Maximum relative rate of decomposition of stable pool, y^{-1}	0.015
C:N ratio for substrates moving to the labile pool	10.0
C:N ratio for substrates moving to the stable pool	20.0
Fraction of C decomposed from labile that is transferred to the stable pool	0.10
Growth efficiency, i.e fraction of decomposed carbon incorporated to the microbial biomass	0.125
Carbon concentration of the biomass	0.40
C:N ratio of roots	30.0
C:N ratio of rhizodeposition	20.0
C:N ratio of straw	100.0
C:N ratio of farmyard manure	25.0
C:N ratio of green manure	15-20

	Rice	Wheat	Jute	Cowpea
Crop				
Light use efficiency, g biomass MJ^{-1}	3.0	3.0	2.5	2.2
Base temperature, °C	8.0	0.0	8.0	10.0
Maximum leaf area, $m^2\ m^{-2}$	6.0	6.0	6.0	6.0
Maximum N concentration, %	3.0	4.0	3.0	5.0
Critical N as a fraction of maximum N	0.4	0.4	0.4	0.4
Maximum root depth, m	0.8	1.5	0.8	0.8
Nitrogen recovery fraction	0.3	0.5	0.5	0.5
Faction of roots in total biomass	0.1	0.1	0.1	0.1
Faction of rhizodeposition in total biomass	0.15	0.15	0.15	0.15
Fraction of dead leaves in total above ground biomass	0.2	0.2	0.2	0.2
Fraction of root (weight) present in the upper (15 cm) layer of soil	0.6	0.5	0.6	0.6
Fraction of root (weight) present in the lower (15-30 cm) layer of soil	0.2	0.2	0.2	0.2
Harvest Index	0.4	0.4	0.25	1.0
Management				
Scaling factors – for relative rate of decomposition				
Puddling	1.0	-		
Non-puddling	0.9	-		
Conventional –tillage	-	1.0		
No-tillage	-	0.9		

CHAPTER 6

General discussion

The broad objective of this study was to evaluate the consequences of intensification of rice-based production systems on soil C and N dynamics, and their effects on crop yields, with special emphasis on the Indo-Gangetic Plains. The specific objective was to develop a summary simulation model for these rice-based cropping systems that allows analysis of the relation between soil organic matter (SOM) and yield formation.

As a start, we reviewed literature on published SOM models and analyzed their underlying principles with respect to their applicability to the rice-based production systems (Chapter 2). Models have been developed with different objectives for a wide variety of agro-ecological environments, and represent various categories ranging from simple analytical (Yang and Janssen, 2000) to detailed comprehensive models (Mueller et al., 1996). The models include different components of the system (soil microbial dynamics, soil water, heat and N dynamics, organic C and N dynamics, crop growth, etc.) in various combinations and at different levels of integration. Explanatory models (e.g. DNDC, ANIMO, APSIM), generally operating at a daily time step, describe many of the processes in detail, whereas summary models (e.g. CENTURY, RothC), operating at a larger time step (monthly), only comprise the essential features belonging to higher levels of integration.

In Chapters 3 and 4, different approaches for modeling different components of the system (SOM, soil and crop) are discussed in isolation, followed by their combination in a summary model of the whole system in Chapter 5. This chapter discusses C and N dynamics at a broader scale and it also discusses modeling approaches with reference to the previous chapters.

Since a model is a simplified representation of the system, it comprises only the most crucial relations that determine the behavior of the system. Therefore, selection of the processes to be included in the model was guided by the purpose of the model. Soil organic matter and its dynamics are highly complex in reality, comprising everything from the last minute microbe to persistent humified material that may be millennia old (Janzen, 2006). This complexity is also illustrated by the chaotic organization of different organic components in the soil in terms of physical (complexed and uncomplexed with the mineral fraction) and chemical (carbohydrates, proteins, cellulose, and lignin) properties (Six et al., 2000; 2002; 2004; Gregorich et al., 2004). Representing such a complex heterogeneous system in a model needs some kind of rather arbitrary classification in a number of ‘pools’. For the specific objective of developing a summary model for long-term dynamics of soil organic C and N, representation of SOM in two (arbitrary) pools (labile and stable) has been selected. A first problem in this approach is the uncertainty associated with quantification of the sizes of these pools, i.e. partitioning of the measured SOM between the two. Since no fractionation procedures proposed so far have resulted in identification of meaningful pools for modelling of C and N dynamics (Olk and Gregorich, 2006), an indirect estimation method is inevitable. Wolf and Van Keulen (1989) assumed equilibrium between the labile and stable pools, characterized by identical rates of transfer from the labile pool to the stable pool and vice-versa, so that their ratio can be calculated from the ratio of the time constants of conversion of both pools. However, initial runs with our model showed that the results did not agree with this assumption, especially for soils that before the start of the experiment were under natural vegetation: these soils appeared to be characterized by a higher proportion of labile organic matter. Since SOM quantity and quality are dependent on land use history (Christensen and Johnston, 1997; Pulleman et al., 2000), we used an empirical relation based on the number of years under cultivation, derived from the Great Plains in the USA (Williams, 1995). An alternative approach was applied by Milne et al. (2006; 2007) in a study to estimate the soil organic carbon (SOC) stock in the Indo-Gangetic Plains. They initialized the pools at equilibrium and ran the model for a number of years beforehand to obtain the initial conditions for the actual simulation. They divided the land use history in the IGP in four periods: the equilibrium period (under native vegetation), base land use (corresponding to the start of the major land use change from natural to cultivation), recent land use (corresponding to the start of the green revolution) and current land use (corresponding to the past ten to fifteen years). They used a variety of sources such as old governmental statistical bulletins, research reports and global data sources to acquire these data. It appeared that 'collecting historical data was the most difficult part of the study'.

In developing the model, many selected processes had to be simplified to meet its objectives (Chapter 5). For example, we assume that fresh residues, added to the fresh organic carbon (FOC) pool, decompose almost completely within the time step of 0.2 y. Many laboratory and field studies have shown that a major portion of fresh organic substrates, consisting largely of carbohydrates and cellulose, vanishes within a short time period. Carbon added to soil as glucose disappeared within one to three days (Van Veen et al., 1985; Ladd et al., 1992; Saggar et al., 1994). Seventy to eighty percent of the cellulose has been shown to decompose in 90-120 days (Zunino et al., 1982; Sørensen, 1983). Some studies (Henin and Dupuis, 1945; Kortleven, 1963; Kolenbrander, 1969; Sauerbeck and Gonzalez, 1977; Andrén and Katterer, 1997) have shown that 12.5-49% of the carbon added remained one year after its application, depending on the quality of the material added. However, most of these studies have been conducted under temperate conditions. Even though the processes governing SOM dynamics in tropical agro-ecosystems are not different from those in temperate systems, the rates of the processes are higher (De Ridder and Van Keulen, 1990; Yang, 1996; Van Keulen, 2001). Therefore, in the model we assume that all carbohydrates and cellulose are decomposed within the time period of 0.2 y and part of the lignin remains.

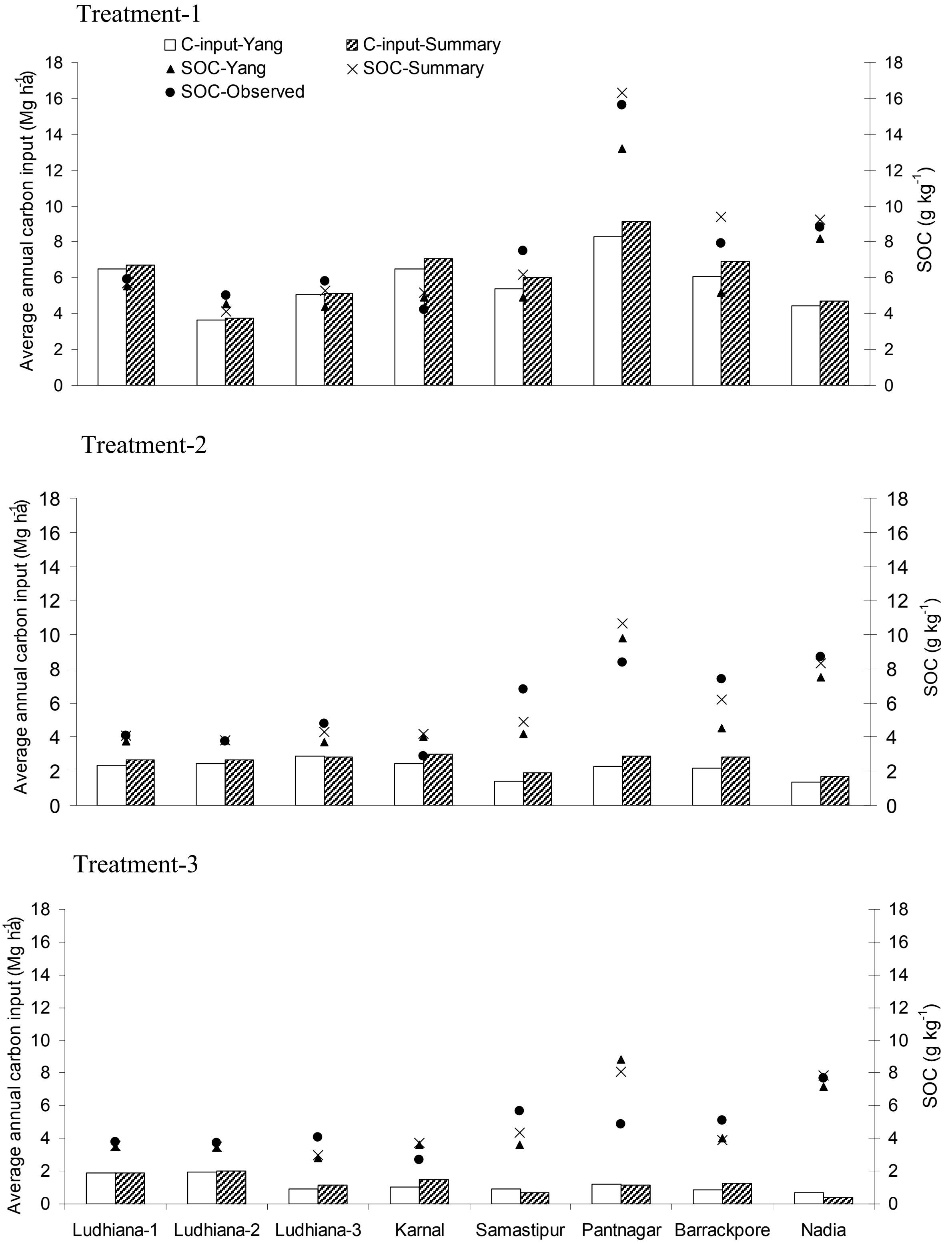
Soil water and N dynamics are also described in a simplified way. Since the rice crop is grown generally under flooded conditions and 80% of the wheat in the IGP is under irrigation, we assume that crops do not experience water stress under normal management. However, soil moisture status is important with respect to C and N dynamics. The end products of the C and N transformations in flooded soils are different from those in aerobic soils, as CO_2 may be further reduced to methane and N may be transformed to N_2O and N_2 under anaerobic conditions. Assuming either of two moisture situations, i.e. field capacity or saturation, allows representation of the difference between rice and an aerobic crop like wheat. Nitrogen losses from applied fertilizers are site-specific and may vary widely, depending on soil texture, pH, moisture conditions, timing, type and method of fertilizer application (De Datta, 1986). The different transformation processes are integrated in a gross ‘recovery fraction’, i.e. the proportion of the fertilizer-N taken up in the aboveground plant components. This appears an adequate approach for a long-term model (cf. Parton et al., 1987) .

Identifying the boundary conditions of the system and defining its domain of application is an import aspect of model development. Considering the objective of analyzing the relation between SOM and yield formation, we restricted the soil depth to 30 cm, as most of the SOM and a major proportion of the roots are located in this soil layer.

The descriptive relationships and parameters in the model need to be adapted when the processes included in the model are to be extrapolated outside the domain (spatial and temporal) for which it is intended. For instance, the growth efficiency of microbes (the part of decomposed carbon that becomes part of the microbial biomass) is around 0.5 (Seligman and Van Keulen, 1981). In the summary model, where a time step of 0.2 y is considered, a value of 0.125 has been adopted, assuming three life cycles for the microbes in this period.

Our limited understanding of the system makes calibration an essential part of model development. In principle, calibration is the process in which model results are fitted to the observations by tuning its parameter values. In the calibration procedure, however, 'ignorance' or lack of insight in the system, that may have led to inaccuracies in model structure, may be confounded through adaptation of parameter values. The quality of the data used for calibration is therefore important for setting the model parameter values. Data from long-term experiments sometimes may lack consistency in the approaches used in experimental design and analytical methods, for instance due to replacement of the responsible researchers. Such problems can hardly be assessed when collecting data from literature, making data quality assessment extremely difficult.

A calibrated model should be able to reproduce field observations from an independent data set to increase confidence in the model. Model results may also be compared with those of another model (a simpler or a more complex model) to increase insight in the relative importance of certain processes. We compared (Figure 1) the results of the summary model (Chapter 5) and Yang's model (Chapter 3) using the same set of data collected at various sites in the IGP. For Ludhiana-1, calculated carbon inputs for both models were similar, as were final SOC values that were also comparable to the observations for all treatments. For Ludhiana-2, carbon inputs and final SOC values for both models were similar in all three treatments. However, both models underestimated the final SOC values in Treatment-1 (fertilizers with organic amendments). The higher carbon input in Treatment-3 (without fertilizer or any organic amendments) for Ludhiana-3 in the summary model is due to overestimation of yields, especially for rice. Final SOC values were underestimated in both models in all three treatments. For Karnal, the summary model calculated higher carbon inputs than Yang's model, due to its consistent overestimation of biomass yield. In contrast, for Samastipur, the models underestimated final SOC values in all treatments. For Pantnagar, results were mixed: final SOC content in Treatment-1 was underestimated by Yang's model, and satisfactorily reproduced by the summary model, while in Treatment-2 (with mineral fertilizers) and Treatment-3 it was overestimated by both models. Calculated annual carbon inputs for Treatment-1 and Treatment-2 were higher in the summary model, and almost equal in the two models for Treatment-3. The higher values in the summary model were associated with overestimation of crop yields. Yang's model underestimated final SOC values for Barrackpore in all three treatments. On the other hand, the summary model underestimated SOC in Treatment-2 and Treatment-3, and overestimated it in Treatment-1, associated with a consistent overestimation of crop yields. For Nadia, model-calculated final SOC values were



Treatment-1

Treatment-2

Treatment-3

Figure 1. Comparison of carbon inputs and final SOC values calculated by Yang’s model and the summary model for various sites, in comparison to observed SOC (Treatment 1 corresponds to fertilizers with organic amendments; Treatment-2 with mineral fertilizers and Treatment-3 is without mineral fertilizer or any organic amendments).

comparable to the observations, with closer agreement for the summary model results. In general, both models satisfactorily reproduced the observed trends in SOC, allowing to some extent, identification of the reasons for similarities and variations in the observed results. However, the deviations in specific situations indicate that our understanding of the system is still incomplete.

Model results in general show that observed SOC and N are adequately reproduced by the model for most sites, although yields are deviating at some sites. These deviations could be attributed to various factors that are mostly site-specific. For example, for Karnal and Samastipur, both models overestimated and underestimated final SOC values, respectively (Figure 1). In Karnal, soil sodicity may have played a role, whereas in Samastipur, $CaCO_3$ may have had a role in protecting SOM. Such effects are not accounted for in either of the two models. In a few sites in the IGP (Pantnagar, Ludhiana-1, and Ludhiana-3) deficiency of macronutrients other than N (P and K) and/or micro-nutrients (Zn) might have played a role in yield formation. However, we did not include the dynamics of these elements, as we concentrated on the role of N in the relation between SOM and yield, although, in principle, a comprehensive modeling approach needs to consider all necessary components relevant to a system.

We did not include some other processes that may be relevant to rice-based cropping systems in general, such as quality changes (phenolic and humic) in organic matter and the 'chemical' immobilization of N (Chapter 1). We have not encountered (a) situation(s) that would suggest that quality changes did play a role. It may thus well be that such quality changes are relevant only for continuously flooded rice systems (Olk et al., 1996; 2000). In contrast to continuously flooded rice systems, in alternating rice-aerobic cropping systems decomposition is enhanced due to stimulation of microbial activity under consecutive wetting and drying cycles. The model did not include this effect, since it is of short-term significance only (Powlson et al., 2001).

Following satisfactory validation, sensitivity analysis is useful to analyze the response of model results to variations in its different components. It allows identification of the processes that are important and need to be investigated through experimental research in the field or the laboratory. It also increases insight in the importance and sensitivity of the assumptions made in the model with regard to the behavior of the system.

Following proper validation, the model can be applied to investigate real-world problems and to formulate scenarios to extrapolate model results. Application of the model to investigate the role of SOM in crop yield formation showed that the contribution of SOM to total crop N uptake varied from as low as 20% in fertilized treatments to as high as of 80% in some unfertilized treatments. Simulated crop yields showed no correlation to SOC-content when N supply from SOM was less than 35% of total N uptake, and was linearly correlated to SOC-content when N-contribution from SOM was higher. Hence, the model based on current knowledge about the processes of soil C and N dynamics and crop growth for the different sites, does not allow to draw definite conclusions with respect to the role of SOM in the observed decline in crop yield in the IGP.

The model can be used to explore 'what if' scenarios, as illustrated in this study in exploring the long-term consequences of adoption of innovative (resource conservation) technologies such as dry seeding and no-tillage on soil organic matter contents and crop yields in the IGP (Chapter 5).

This study has shown that, although the processes involved in carbon and nitrogen transformations in soil are complex, a relatively simple model can adequately describe their dynamics in rice-based cropping systems. The model could be further applied to answer strategic questions and to evaluate alternative technologies. For instance, to analyze the possibilities for diversification (including more leguminous crops or substituting rice and wheat with other crops) of the current rice-based cropping systems and its implications for sustainability and food production at regional level.

Our study has shown that modeling is an effective tool for summarizing existing knowledge for the purpose of analyzing agricultural production systems and to explore the consequences of technological change. However, it made also clear that our understanding of the dynamics of soil organic matter in rice-based cropping systems and its impacts on crop yields in these systems in the IGP is still insufficient to draw definite conclusions about their quantitative relations.
To enhance the applicability of the model, further improvements are necessary. We have formulated some ideas below.

Suggestions for future research

1. An improved experimental method to assess the labile and stable pools is required, as land use history is seldom known in most of the situations.
2. The model considers the effect of pH on SOM dynamics in a rather rudimentary way, which appears to work reasonably well for neutral to higher pH soils.

However, for soils of low pH, the relation needs to be re-assessed, as the simulations for the low-pH soil in Palampur consistently underestimated SOC.

3. The effects of sodicity and $CaCO_3$ on SOM dynamics need further attention and should be included in the model for its wider applicability.
4. The effect of tillage on C and N dynamics in the model at present is described in a qualitative way. A quantitative description that relates tillage to soil (physical) properties that in turn should be related to organic matter transformations is needed to explicitly express the impact of zero-tillage.
5. For a more comprehensive sustainability assessment of rice-based cropping systems, the model needs to consider also the dynamics of other (than N) macro- and micro-nutrients in soil and plant. Deficiency of other macro- or micro-nutrients may affect crop yields and thus carbon input into the soil.

References

Andren, O. and Katterer, T., 1997. ICBM: the introductory carbon balance model for exploration of soil carbon balances. Ecological Applications 7, 1226-1236.

Christensen, B. and Johnston, A.E., 1997. Soil organic matter and soil quality-lessons learned from long-term experiments at Askov and Rothamsted. In: Gregorich, E. G. and Carter, M. R. (Eds.), Soil quality for crop production and ecosystem health. Developments in Soil Science 25, Elsevier, Amsterdam, pp. 399-430.

De Datta, S.K., 1986. Improving nitrogen fertilizer efficiency in lowland rice in tropical Asia. Fertilizer Research 9, 171-186.

De Ridder, N. and Van Keulen, H., 1990. Some aspects of the role of organic matter in sustainable intensified arable farming systems in the West-African semi-arid tropics (SAT). Fertilizer Research 26, 299-310.

Gregorich, E.G., Beare, M.H., McKim, U.F. and Skjemstad, J.O., 2006. Chemical and biological characteristics of physically uncomplexed organic matter. Soil Science Society of America Journal 70, 975-985.

Henin, S. and Dupuis, M., 1945. Essai de bilan de la matière organique du sol. Annals of Agronomy 15, 17-29.

Janzen, H.H., 2006. The soil carbon dilemma: Shall we hoard it or use it? Soil Biology and. Biochemistry 38, 419-424.

Kolenbrander, G.J., 1969. De bepaling van de waarde van verschillende soorten organische stof ten aanzien van hun effect op het humusgehalte bij bouwland. Instituut voor Bodemvruchtbaarheid, Haren, The Netherlands, 17 pp.

Kortleven, J., 1963. Kwantitatieve aspecten van humusopbouw en humusafbraak Verslagen van Landbouwkundige Onderzoekingen 69.1, Pudoc, Wageningen, The Netherlands, 109 pp.

Ladd, J.N., Jocteur-Monrozier, L. and Amato, M., 1992. Carbon turnover and nitrogen transformations in an alfisol and vertisol amended with 14C-glucose and 15N-ammonium sulfate. Soil Biology and Biochemistry 24, 359-371.

Mueller, T., Jensen, L.S., Hansen, S. and Nielsen, N.E., 1996. Simulating soil carbon and nitrogen dynamics with the soil-plant-atmosphere system model DAISY. In: Powlson, D.S., Smith, P. and Smith, J.U. (Eds.), Evaluation of soil organic matter models using existing long-term datasets. Proceedings of the NATO Advanced Research Workshop, NATO ASI Series I, Vol. 38, Springer Verlag, Berlin, pp. 275-281.

Milne, E., Easter, M., Cerri, C.C., Paustian, K. and Williams, S., 2006. Assessment of soil organic carbon stocks and change at national scale. The University of Reading, UK and the GEF implementing agency, The United Nations Environmental Program, 172 pp.

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. and Rawajfih, Z., 2007. An increased understanding of soil organic carbon stocks and changes in non-temperate areas: National and global implications. Agriculture, Ecosystems & Environment (In Press).

Olk, D.C. and Gregorich, E.G., 2006. Overview of the Symposium Proceedings, "Meaningful pools in determining soil carbon and nitrogen dynamics". Soil Science Society of America Journal 70, 967-974.

Olk, D.C., Brunetti, G. and Senesi, N., 2000. Decrease in humification of organic matter with intensified lowland rice cropping: a wet chemical and spectroscopic investigation. Soil Science Society of America Journal 64, 1337-1347.

Olk, D.C., Cassman, K.G., Randall, E.W., Kinchesh, P., Sanger, L.J. and Anderson, J.M., 1996. Changes in chemical properties of organic matter with intensified rice cropping in tropical lowland soil. European Journal of Soil Science 47, 293-303.

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal 51, 1173-1179.

Powlson, D.S., Hirsch, P.R. and Brookes, P.C., 2001. The role of soil microorganisms in soil organic matter conservation in the tropics. Nutrient Cycling in Agroecosystems 61, 41-51.

Pulleman, M.M., Bouma, J., Van Essen, E.A. and Meijles, E.W., 2000. Soil Organic Matter Content as a Function of Different Land Use History. Soil Science Society of America Journal 64, 689-693.

Saggar, S., Tate, K.R., Feltham, C.W., Childs, C.W. and Parshotam, A., 1994. Carbon turnover in a range of allophanic soils amended with 14C-labelled glucose. Soil Biology and Biochemistry 26, 1263-1271.

Sauerbeck, D.R. and Gonzalez, M.A., 1977. Field decomposition of carbon-14-labelled plant residues in various soils of the Federal Republic of Germany and Costa Rica. Soil organic matter studies 1. Proceedings of a Symposium organized by IAEA, FAO and Agrochimica, Braunschweig, Germany, pp. 159-170.

Seligman, N.G. and Van Keulen, H., 1981. PAPRAN: a simulation model of annual pasture production limited by rainfall and nitrogen. In: Frissel, M. J. and van Veen, J. A. (Eds.) Simulation of nitrogen behavior of soil plant systems. Pudoc, Wageningen, The Netherlands, pp. 192-220.

Six, J., Paustian, K., Elliott, E.T. and Combrink, C., 2000. Soil structure and organic matter. I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Science Society of America Journal 64, 681-689.

Six, J., Feller, C., Denef, K., Ogle, S.M., Sa, J.C.D. and Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils-effects of no-tillage. Agronomie 22, 755-775.

Six, J., Bossuyt, H., Degryze, S. and Denef, K., 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Research 79, 7-31.

Sørensen, L.H., 1983. Size and persistence of the microbial biomass formed during the humification of glucose, hemicellulose, cellulose, and straw in soils containing different amounts of clay. Plant and Soil 75, 121-130.

Van Keulen, H., 2001. (Tropical) soil organic matter modelling: problems and prospects. Nutrient Cycling in Agroecosystems 61, 33-39.

Van Veen, J.A., Ladd, J.N. and Amato, M., 1985. Turnover of carbon and nitrogen through the microbial biomass in a sandy loam and a clay soil incubated with 14C-glucose and 15N-ammonium sulfate under different moisture regimes. Soil Biology and Biochemistry 17, 747-756.

Wolf, J. and Van Keulen, H., 1989. Modeling long-term crop response to fertilizer and soil nitrogen. II. Comparison with field results. Plant and Soil 120, 23-38.

Williams, J.R., 1995. The EPIC model. In: Singh, V. P. (Ed.), Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, CO, pp. 909-1000.

Yang, H.S., 1996. Modelling organic matter mineralization and exploring options for organic matter management in arable farming in Northern China. PhD Thesis, Wageningen Agricultural University, Wageningen, The Netherlands, 159 pp.

Yang, H.S. and Janssen, B.H., 2000. A mono-component model of carbon mineralization with a dynamic rate constant. European Journal of Soil Science 51, 517-529.

Zunino, H., Borie, F., Aguilera, S., Martin, J.P. and Haider, K., 1982. Decomposition of 14C-labeled glucose, plant and microbial products and phenols in volcanic ash-derived soils of Chile. Soil Biology and Biochemistry 14, 37-43.

Summary

The Indo-Gangetic Plains (IGP), with its plentiful natural resources, contributes a major proportion (42%) to food grain production in India. However, the still growing population of the country requires another 40% increase in food grain production above the present 210 Tg per annum when the population reaches 1.6 billion by 2050. The limited scope for further expansion in area creates pressure on the land under cultivation to produce more to meet this future food demand. However, intensive cropping in the region in the last decades has led to a ‘yield stagnation’, associated with a decrease in the productivity of various inputs, and even a decline in crop yields in some parts of the IGP. One of the major reasons speculated for such a stagnation is the decline in soil organic matter (SOM) quality and quantity and the associated decrease in N availability for the crop. The objective of this study was to develop a summary model to evaluate the consequences of intensification in rice-based cropping systems on soil C and N dynamics and their effects on crop yields.

At first, an extensive review has been made of published SOM models with emphasis on their objectives and underlying principles to identify approaches suitable for modeling the long-term dynamics in rice-based cropping systems. The review showed that in modeling SOM dynamics basically two approaches are followed, both based on the principle of first order kinetics. In the first approach, SOM is treated as a single entity with a relative decomposition rate defined either as constant or as a function of time since application. In the second approach, SOM is partitioned into a number of pools, each of which decomposes with its own characteristic relative decomposition rate.

Following this evaluation of a number of existing models, we selected a simple analytical model to evaluate long-term experimental (LTEs) datasets collected from different parts of the IGP. This model belongs to the first category, with a relative decomposition rate defined as a function of time since application. The model needs two parameters, the initial relative decomposition rate (R) and the rate of ageing (S) of a substrate. Furthermore, the model includes a temperature correction factor (f). The model has been used to calculate soil carbon dynamics for various sites in the IGP, based on estimated carbon inputs and their rate of decomposition. The model satisfactorily reproduced the observed soil organic carbon (SOC) values.

Since the carbon inputs and nitrogen uptake from the soil in agricultural land use systems are determined by crop/cropping system performance, an adequate representation of crop growth in relation to soil and crop nitrogen was necessary to obtain insight in the short term processes. Therefore, a crop model, LINTUL3, based on the light use efficiency approach, was developed for rice and was calibrated and validated with datasets from the International Rice Research Institute (IRRI) in the Philippines and the Central Rice Research Institute (CRRI) in India. LINTUL3, an extended version of a crop growth model for potential (LINTUL1) and water-limited (LINTUL2) conditions, describes nitrogen demand and uptake by the crop in detail and soil nitrogen supply in a simplified form. Following model calibration, results of model validation were in satisfactory agreement with the observations.

After studying the different components of the system (SOM and crop) in isolation, the obtained knowledge was combined to develop a summary model. The summary model for long-term dynamics of SOM considers the complexity intrinsic to SOM, its interaction with the physical environment and its effects on crop performance. The model consists of three modules, SOM, SOIL and CROP, dealing with the dynamics of soil organic matter, soil moisture and crop growth, respectively.

The complex nature of SOM is simplified by distinguishing two soil carbon pools, *labile* and *stable*, in addition to a fresh organic carbon (FOC) pool. Crop residues from each season are added to the FOC pool, and the fraction of FOC that becomes part of the soil organic carbon store depends on the quality (lignin content) of the added substrates. The labile and stable pools decompose according to first order kinetics. Their actual rates of decomposition are influenced by environmental conditions (temperature, moisture, texture, pH, etc.) and management practices (tillage, puddling, etc.). Effects of these factors are interactive. Therefore, their influence on the relative rates of decomposition is expressed in a multiplicative way.

The SOIL module considers only two upper soil layers (15 cm each), that are considered most important agronomically. Soil water content and temperature, the two major environmental factors influencing carbon and nitrogen dynamics, are not simulated dynamically. Rather, they are (for water) defined as a function of crop management and (for temperature) set to the mean seasonal air temperature. Soil water is assumed to be either at field capacity or at saturation, for irrigated and flooded crops, respectively. Inorganic nitrogen in the soil originates from mineralization from SOM, fertilizer application, and dissolved N in irrigation water and rainfall. Other potential sources such as biological N-fixation are not considered in the model.

The summary CROP module is rooted in the detailed model (LINTUL3) described for rice. The CROP module calculates potential and actual biomass production, leaf area index (LAI), evapotranspiration, total N demand, actual N uptake and N stress. Actual biomass production is first partitioned over above- and belowground components. An exogenously defined harvest index (HI) is applied to calculate (grain) yield from aboveground biomass. The basic structure of the CROP module is identical for all crops, as the basic processes underlying biomass production do not differ among crops. Therefore, the module represents a flexible framework for application to different crops in different cropping systems with only the need to adapt crop-specific parameters.

The summary model satisfactorily reproduced the observed trends in SOM, total soil-N and crop yields for various sites under different fertilizer and manure treatments. The model results show that SOM-content is not always a direct measure of the nitrogen supplying capacity of a soil, and the importance of SOM as a nitrogen source for crops should be considered relative to the supply from other sources. In the model results, the contribution from SOM to total crop N uptake varied from about 20% in fertilized treatments to a maximum of 80% in some unfertilized treatments. Simulated crop yields showed no correlation to SOM-content when N supply from SOM was less than 35% of the total N uptake, whereas it was linearly correlated to SOM-content when the N-contribution from SOM was higher. The higher the proportion of total N-uptake from SOM, the stronger its impact on crop yield.

The model developed is an effective tool for scenario analyses, in which long-term consequences of adoption of innovative technologies are explored. Model results show that innovative management systems such as direct seeded rice (DSR) and zero-tilled wheat (ZTW) result in higher crop yields, SOC and total soil-N contents, and in reduced methane emissions for the various sites considered in the study.

Although the processes involved in carbon and nitrogen transformations in soil are complex, this study has shown that a relatively simple model can adequately describe their dynamics in (rice-based cropping) systems as a whole. The model could be further applied to answer strategic questions and to evaluate alternative technologies for the current cropping systems for policy decisions in the Indo-Gangetic Plains of India.

Samenvatting

De laagvlakte gevormd door de Indus en de Ganges, de zogenoemde Indo-Gangetic Plains (IGP), is rijk aan natuurlijke hulpbronnen en draagt sterk bij (42%) aan de voedselgraanproductie in India. De voortgaande groei van de bevolking echter eist nog eens een toename van 40 procent in de voedselgraanproductie bovenop de huidige 210 Tg, als de bevolkingsomvang 1,6 miljard mensen bereikt in 2050. De mogelijkheden voor uitbreiding van het huidige landbouwareaal, om aan deze toekomstige extra vraag te voldoen, zijn beperkt. Daarnaast heeft de in de laatste decennia geïntensiveerde landbouw in het gebied geleid tot stagnatie van de opbrengsten per hectare door afname van de productiviteit van verschillende productiefactoren, en zelfs tot een afname in gewasopbrengsten in sommige delen van de IGP. Eén van de belangrijkste veronderstelde redenen voor het stagneren van de opbrengsten is de afname in kwaliteit en kwantiteit van organische stof in de bodem en de daarmee samenhangende verminderde stikstofbeschikbaarheid voor het gewas. De doelstelling van deze studie was een samenvattend model te ontwikkelen om de gevolgen van intensivering van op rijstverbouw gebaseerde productiesystemen op de bodemkoolstof- en bodemstikstofdynamiek te evalueren, en hun effect op gewasopbrengsten.

Allereerst is een uitgebreide studie gemaakt van bestaande organische stof modellen van de bodem, met speciale aandacht voor de doelstellingen en onderliggende principes, teneinde geschikte benaderingen te identificeren om de lange-termijn dynamiek van organische stof in de bodem in op rijstverbouw gebaseerde gewassystemen te modelleren. Het overzicht laat zien dat bij het modelleren van organische stof dynamiek in principe twee typen benaderingen worden gevolgd, beide gebaseerd op eerste orde kinetiek. In de eerste benadering wordt organische stof als één geheel beschouwd met een relatieve afbraaksnelheid die ofwel constant wordt verondersteld ofwel als functie van de tijd vanaf toediening van de organische stof wordt berekend. In de tweede benadering wordt organische stof onderverdeeld in een aantal componenten, waarbij voor elke component een karakteristieke relatieve afbraaksnelheid wordt gedefinieerd.

Gebaseerd op deze evaluatie van bestaande organische stof modellen, hebben we een eenvoudig analytisch model geselecteerd om resultaten van langlopende experimenten, uit verschillende delen van de IGP, te evalueren. Dit analytische model gebruikt de eerste benadering, waarbij de relatieve afbraaksnelheid wordt berekend als functie van de tijd vanaf toediening van de organische stof. Er zijn twee parameters nodig voor het model: de initiële relatieve afbraaksnelheid (R) en de verouderingssnelheid (S) van een substraat. Verder bevat het model een correctiefactor voor de temperatuur (f). Het model is gebruikt om de bodemkoolstofdynamiek op diverse locaties in de IGP te berekenen, uitgaande van de geschatte koolstofaanvoer via gewasresten en hun afbraaksnelheid. Berekende organische koolstofgehalten in de bodem kwamen redelijk overeen met de waarnemingen.

Omdat de stikstofopname uit de grond en de koolstofaanvoer naar de grond in agrarische landgebruiksystemen wordt bepaald door het functioneren van het gewas/gewassysteem, was een adequate beschrijving nodig van gewasgroei in samenhang met de stikstofdynamiek in bodem en gewas, teneinde inzicht te verkrijgen in de korte termijn processen. Hiertoe werd een gewasgroeimodel voor rijst ontwikkeld, LINTUL3, gebaseerd op het concept van de lichtgebruiksefficientie. Het model werd gecalibreerd en gevalideerd met behulp van experimentele gegevens van het IRRI (International Rice Research Institute) op de Fillippijnen en het CRRI (Central Rice Research Institute) in India. LINTUL3 is een uitbreiding van een gewasgroeimodel voor potentiële groei (LINTUL1) en watergelimiteerde groei (LINTUL2). Het model bevat een gedetailleerde beschrijving van de vraag naar stikstof van het gewas en de opname, terwijl de stikstofhuishouding van de bodem in een meer eenvoudige vorm wordt beschreven. Na calibratie van het model, was de overeenkomst tussen de modelresultaten en de waarnemingen bevredigend.

Na afzonderlijke bestudering van de verschillende componenten van het systeem (organische stof en gewas), werd de verkregen kennis gecombineerd om een samenvattend model te ontwikkelen. Het samenvattend model voor de berekening van de lange termijn organische stof dynamiek in de bodem houdt rekening met de intrinsieke complexiteit van organische stof, haar interacties met de omgeving en haar effecten op het functioneren van het gewas. Er worden drie modules onderscheiden, SOM, SOIL en CROP, die respectievelijk de dynamiek behandelen van de organische stof, het vochtgehalte in de bodem en de gewasgroei.

De complexe samenstelling van bodemorganische stof is vereenvoudigd weergegeven door in de bodemkoolstof schematisch twee componenten te onderscheiden, *labiele* en *stabiele* koolstof, naast een component die verse organische koolstof vertegenwoordigt (FOC). Elk seizoen worden de gewasresten toegevoegd aan de FOC voorraad. Het deel van de FOC voorraad dat in bodemorganische koolstof wordt omgezet hangt vervolgens af van de kwaliteit (ligninegehalte) van het toegevoegde substraat. De labiele en stabiele koolstofvoorraden breken volgens eerste orde kinetiek af. Hun actuele afbraaksnelheden hangen af van omgevingscondities (temperatuur, vochtgehalte, textuur, pH, etc.) en grondbewerkingshandelingen (ploegen, puddelen, etc.). Aangezien deze factoren elkaar beïnvloeden, wordt hun effect op de relatieve afbraaksnelheden op een multiplicatieve manier berekend.

De bodemmodule (SOIL) modelleert uitsluitend de twee bovenste lagen (van elk 15 cm), omdat deze uit landbouwkundig oogpunt het belangrijkst zijn. Bodemvochtgehalte en temperatuur zijn de twee belangrijkste omgevingsfactoren waardoor koolstof- en stikstofdynamiek worden beïnvloed. Zij worden niet dynamisch gesimuleerd; bodemvochtgehalte hangt af van het geteelde gewas, en temperatuur is gelijkgesteld aan de gemiddelde seizoenstemperatuur. Bodemvochtgehalte wordt gelijk gesteld aan veldcapaciteit voor geïrrigeerde gewassen, of aan verzadiging voor bevloeide gewassen. Anorganische bodemstikstof is afkomstig van mineralisatie van organische stof, bemesting en van in irrigatiewater en regen opgeloste stikstof. Andere potentiële stikstofbronnen zoals biologische stikstofbinding worden niet in het model beschouwd.

De samenvattende gewasgroeimodule (CROP) is gebaseerd op het gedetailleerde, voor rijst beschreven, LINTUL3 model. De module berekent zowel potentiële als actuele biomassaproductie, bladoppervlakteindex (LAI), evapotranspiratie, totale stikstofvraag, actuele stikstofopname en een eventueel stikstofgebrek. De actuele biomassaproductie wordt eerst verdeeld over boven- en ondergrondse gewasdelen. Vervolgens wordt een exogeen gedefinieerde oogstindex (HI) gebruikt om de (graan-) opbrengst te berekenen. De basisstructuur van de gewasmodule geldt voor alle gewassen, omdat de onderliggende productieprocessen voor de verschillende gewassen gelijk zijn. Daarom vormt de module een flexibel raamwerk, dat toegepast kan worden op verschillende gewassen in verschillende gewassystemen, met als enige voorwaarde dat gewasspecifieke parameters aangepast moeten worden.

Het samenvattende model reproduceert op herkenbare wijze de waargenomen trends in bodemorganische stof, totale bodemstikstof en gewasopbrengsten voor diverse locaties en onder verschillende kunstmest- en dierlijke mestgiften. De modelresultaten laten zien dat het organisch stofgehalte van de bodem niet altijd een directe maat is voor de stikstofleveringscapaciteit van een bodem. Daarom moet het belang van bodemorganische stof als stikstofbron voor gewassen vergeleken worden met de aanvoer vanuit andere stikstofbronnen. Uit de modelresultaten bleek dat de bijdrage van bodemorganische stof aan de totale stikstofopname door het gewas schommelde tussen ongeveer 20% in bemeste behandelingen en een maximum van 80% in sommige onbemeste behandelingen. Gesimuleerde gewasopbrengsten waren niet gecorreleerd met het bodemorganisch stofgehalte als de stikstofaanvoer hieruit minder dan 35% van de totale stikstofopname bedroeg, terwijl ze lineair gecorreleerd waren met het bodemorganisch stofgehalte als de stikstofbijdrage hieruit hoger was. Dus hoe hoger het aandeel van de totale stikstofopname uit bodemorganische stof, hoe sterker haar effect op de gewasopbrengst.

Het ontwikkelde model is een effectief instrument voor het doorrekenen van scenario's waarin lange-termijn gevolgen van adoptie van innovatieve technologieën worden geëxploreerd. De modelresultaten laten zien dat alternatieve grondbewerkingstechnieken, zoals direct zaaien van rijst (DSR) en minimale grondbewerking bij tarwe (ZTW), voor diverse locaties in de studie enerzijds leiden tot hogere opbrengsten, organische bodemkoolstofgehalten en totale bodemstikstofgehalten, en anderzijds tot lagere methaanemissies.

Hoewel de processen betrokken bij koolstof- en stikstofomzettingen in bodems complex zijn, heeft deze studie aangetoond dat een relatief eenvoudig model hun dynamiek in (op rijst gebaseerde) gewassystemen als geheel adequaat kan beschrijven. Het model zou verder gebruikt kunnen worden om strategische vragen te beantwoorden en om alternatieve technologieën te evalueren voor de huidige gewassystemen ter ondersteuning van beleidsbeslissingen in de Indo-Gangetic Plains.

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International Symposia, Workshops and Conferences (6 credits)
- 18th World congress of soil science, Philadelphia, USA (2006)
- International symposium on organic matter dynamics in agro-ecosystems; INRA / ESIP, University of Poitiers, France (2007)

Courses in which the PhD Candidate has worked as a Teacher
- Models for forest and nature conservation; INF (2004); 14 days
- Crop ecology; HPC (2005); 7 days

Curriculum vitae

Shibu Ebrahim Muhammed was born in Kerala, India, on May 22, 1974. He was educated at Leo XIII high school and St. Michael's College, Chertala, Alappuzha. He completed his Bachelor's degree in Agriculture from Kerala Agricultural University, Trissur, in 1997. With a Junior Research Fellowship awarded by the Indian Council of Agricultural Research, New Delhi, he pursued his Master's studies in Soil Science at Punjab Agricultural University, Ludhiana, during 1998-2000. On completion, he joined the Centre for Applications of Systems Simulation (CASS) of the Indian Agricultural Research Institute in New Delhi, before starting his PhD in Wageningen University with a fellowship from the Netherlands Organization for Scientific Research, NWO-WOTRO, in October 2002. At the moment, he is employed in the McCaulay institute in Aberdeen where he will work as a Land use change ecosystem modeler.

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