Soil Carbon Dynamics in Different Cropping Systems in Principal Ecoregions of Asia

**K.F. Bronson, K.G. Cassman, R. Wassmann, D.C. Olk,
M. van Noordwijk, and D.P. Garrity**

I. Introduction

A. Land Use in Asia

More than half of the world's population lives in Asia where only 30% of the world's 1,346 million ha of arable land are found (Table 1, FAO 1994). To produce enough food for the rapidly growing population, agricultural land use in Asia has become very intense. Cereal production in Asia makes up half of the world's total. The most important crop is rice, followed by wheat and maize. Double cropping of rice makes up most of the 55% of the harvested irrigated rice area (IRRI 1993). Rice – wheat is a basic rotation practiced on 21 million ha (Woodhead et al., 1994). The area cropped to a rice – maize rotation is smaller than that devoted to rice – wheat, but it is rapidly increasing. Moreover, the rate of conversion of prime riceland for industrial and residential use continues at an alarming rate. In China, Indonesia, and the Philippines, this trend threatens self-sufficiency in cereal production.

B. Rice – Rice Systems

About 520 million tons of rough rice are produced annually. Of this, more than 90% is produced and consumed in Asia and only 4% of global rice production is traded across international borders (IRRI, 1991). As the primary staple food, it provides more than 50% of total calorie intake in many Asian countries.

Rice is a crop adapted to a wide range of environments. In Asia, it is a major crop grown in countries as far as North Korea (44° N) down to Australia (35° S) It is cultivated at elevations ranging from 0 to 2,700 m above sea level. It is produced as an upland crop on sloping land, planted in rainfed lowlands with alternating periods of submerged and aerated soil conditions, and cultivated in irrigated lowland systems in flooded soil. Irrigated rice systems account for 78% of all rice-producing areas (Cassman and Pingali, 1995).

In the 75 million ha harvested in Asia (IRRI, 1993), three major cropping systems exist, mostly in the irrigated rice area. Continuous rice systems with two or three crops each year are practiced on more than 14 million ha, representing nearly 30 million ha of harvested rice. An annual rice – wheat double-crop system occupies another 21 million ha in the Indo – Gangetic plains of south Asia and China (Woodhead et al., 1994). In temperate regions of China, Japan, Korea, and Australia, rice is grown annually under

ISBN 0-8493-7442-1

Table 1. Major land use and cereal production in Asia and the World

	World		Asia	
	Area (10^6 ha)	Production (10^6 t)	Area (10^6 ha)	Production (10^6 t)
Total area	13,422	--	2,758	--
Land area	10,973	--	2,679	--
Agricultural area	4,868	--	1,259	--
Arable and permanent pasture	1,444	--	459	--
Arable land	1,346	--	425	--
Cereals, total	691	1,894	307	903
Rice, paddy	147	527	132	482
Wheat	222	564	87	224
Maize	127	470	39	136
Permanent crops	98	--	34	--
Permanent pasture	3,424	--	800	--
Forested woodland	3,880	--	535	--

(Adapted from FAO, 1994.)

single-crop systems although other crops are sometimes grown in rotation with rice. In all of these systems, however, rice is grown in flooded soil. It is this attribute that makes carbon (C) dynamics of irrigated rice systems unique.

In transplanted rice, fields are flooded before planting and soil is puddled to reduce percolation. Rice is also direct seeded using either wet seeding with pregerminated seed broadcast on a puddled soil surface or dry seeding after normal soil tillage. Both wet- and dry-seeded rice is flooded after seedlings are established. In all cases the saturated soil is covered by a layer of floodwater. Soil redox potential rapidly decreases within 14–28 days after flooding to a steady-state level determined by the amount of readily decomposable organic matter, temperature, and availability of electron acceptors such as NO_3 Mn^{+4}, and Fe^{+3} (Ponnamperuma, 1972). The chemical environment of reduced soil and the extremely limited O_2 supply in the soil-floodwater system have a large influence on the C dynamics of irrigated rice systems.

Annual double- and triple-crop rice systems are the dominant land use systems in tropical lowlands of Asia where irrigation water is available. These are perhaps the most intensive cereal crop production systems in the world because they receive large external subsidies of applied nutrients. Nitrogen fertilizer is the largest single input and net primary production is tremendous. Average irrigated rice yields in 14 Asian countries were 5 t ha^{-1} in 1990 (Cassman and Pingali, 1995). With a typical harvest index of 0.5 (Yoshida, 1981), total annual aboveground dry matter production in the two crops would be 20 t ha^{-1}. In the Long-Term Continuous Cropping Experiment at IRRI in which a triple-crop system is practiced, annual grain production at the beginning of the experiment was 22 t ha^{-1} (IRRI, 1967), representing a net primary production of more than 40 t biomass ha^{-1}. In this experiment, dry season rice yield in 22 cycles declined sharply, but averaged 4.2 and 6.8 t ha^{-1}, for control and fertilized treatments, respectively. Early wet-season rice grain yields were higher at 3.6 and 4.7 t ha^{-1} for the same two treatments, with a slower decline. Late wet-season rice grain yields averaged 2.8 and 3.4 t ha^{-1}, for the control and fertilized treatments, respectively, with an even smaller yield decline (Cassman et al., 1995).

Rice straw management in Asia varies by region. In Southeast Asia, straw is usually burned; in China and South Asia, it is partly recycled through composting (Flinn and Marciano, 1984). When stubble is removed or burned, only the root systems are recycled.

Fertilizer inputs, particularly N, are relatively high in irrigated rice systems. Estimates of annual N fertilizer use on irrigated rice indicate average rates of about 100 kg ha^{-1} (Cassman and Pingali 1995).

C. Rice – Wheat Systems

Rice followed in sequence by wheat is a cropping system dating back thousands of years in South Asia (Woodhead et al., 1994). Since rice and wheat are staple foods in South Asia, their production must keep pace with population growth. Rice is grown during the summer monsoon months while wheat is cultivated during the cool, dry winter. This system is mostly practiced on irrigated land. Of the total 20.9 million ha under this rotation, 9.5, 9.1, 1.4, 0.5, and 0.4 million ha occur in India, China, Pakistan, Bangladesh, and Nepal, respectively. Production of rice and wheat is increasing in northwest India, but grain output in east India, Bangladesh, and Nepal are stagnant or less than the rate of increase in population. Rice yields in parts of China are relatively high under rice – wheat systems, with average grain yields of 7 t ha^{-1} in major areas such as the Yangtze River Valley (IRRI, 1995). Wheat yields are substantially lower.

The level of inputs to rice – wheat cropping systems varies across the region. Fertilizer use has been increasing sharply in northwest India (Abrol and Gill, 1994) and in China (IRRI, 1995), but is still relatively low in the rest of the subcontinent. Green manuring, historically high in China, has decreased from 13 million ha in 1976 to 2.8 million ha in 1989 (Lianzheng and Yixian 1994). Use of farmyard manure (FYM) in the Indian subcontinent has been relatively common historically, but its use is declining too (Hobbs et al., 1992). Straw removal in rice – wheat systems has been the norm for a long time. Burning of straw is becoming more common, especially in northwest India where use of combine harvesters is increasing (Tanaka, 1978; Flinn and Marciano, 1984).

Declining factor productivity on both farmers' fields and on-station experiments is evident in rice – wheat systems. On-station data from long-term experiments in Bhairahawa, Nepal (Regmi, 1994), and in Pantnagar, Uttar Pradesh, India (Nambiar, 1995), indicate alarming yield declines in the rice phase of the rice – wheat system. In Bhairahawa, grain yields of early rice declined sharply during 15 years/cycles, but averaged 0.5 and 3.0 t ha^{-1} for control and fertilized treatment, respectively. Normal rice grain yields were higher at 1.2 and 3.1 t ha^{-1} for the same two treatments, but there was also a declining trend. Wheat grain yields averaged 0.6 and 2.5 t ha^{-1}, for the control and fertilized treatment, respectively, with no significant decline (Regmi, 1994). In China, productivity trends are not as discouraging, although declining productivity has been reported (Byerlee, 1992). However, serious environmental problems as a result of high fertilizer input levels in their intensive cropping systems have been observed. Nitrate contamination of groundwater, for example, is becoming widespread.

D. Upland Systems

In contrast to the intensively used lowlands on which most of the staple foods are produced, extensive land use patterns in the uplands still occur. We adhere to the conventional 'lowland' 'upland' terminology, which does not refer to differences in elevation, but rather to distinctions in drainage, cropping patterns, and soil C dynamics.

The classical 'shifting cultivation' and 'long rotation fallow' systems of the uplands have lost most of their importance for securing food supply and have been replaced by semipermanent conversion of natural forests for agricultural land use. Slash-and-burn methods of forest conversion are held responsible for a considerable share in global C emissions and the loss of biodiversity and have thus become a point of global concern. Extensive areas of Southeast Asia have been transformed from forests into *Imperata* grasslands (Garrity et al., 1993). Major changes in land tenure and accessibility must occur before the same areas are used again. In these upland systems, soil organic matter (SOM) is a key factor in the maintenance of soil fertility and future productive potential. Permanent cropping on large areas of upland soils is only possible through a judicious combination of crop residue management, external nutrient inputs, and possibly inclusion of components with low harvest index such as cover crops or trees. Large parts of the uplands are more suitable for tree crops. In these systems, annual food crops are confined to the early stages of establishing perennial crops such as rubber, oil palm, or fruit trees. Some of these systems have developed out of 'long fallow rotation' systems from the increased share of valuable trees in the regrowth vegetation without excluding regeneration of natural elements. These systems are now called 'agroforests' and are gradually gaining recognition as a sustainable land use option that combines productivity and environmental objectives (Van Noordwijk et al., 1995a).

II. Trends in Soil Organic C Content

A. Continual Cropping and Soil Organic C Levels

Among Asian countries, India has the lowest average concentration of soil organic carbon (SOC) in agricultural soils (Table 2) (Kyuma, 1988), especially in the Indo-Gangetic Plains (Table 3) (Nambiar 1994). These largely alluvial soils are inherently fertile and high in K. However, removal of nearly all crop residues in intensive rice – wheat and rice – maize systems has contributed to the decline in SOC. This decline appears to be continuing at present in many areas, and in places where SOC is 3.0 to 4.0 g kg^{-1}, a near equilibrium at these low levels has been reached. In a few isolated cases, small increases in SOC have been reported in rice – wheat systems where residue is removed (Thakur et al., 1995). Rice-"upland crop" rotations such as rice – wheat or rice – maize generally have lower SOC than strictly rice systems (Tables 3, 4) (Nambiar, 1994; Cheng, 1984).

On the other hand, in double-cropped rice areas, SOC levels are relatively stable, even if manure or straw residue incorporation is not practiced (Tables 3, 4) (Cheng, 1984; Cassman et al., 1995; Nambiar, 1994). Apparently, the nature of two or three flooded rice organic crops, without an upland crop phase grown in aerated soil, is enough to slow down C decomposition. The chemical nature of SOM at these relatively higher soil C levels, however, appears to be altered (Olk et al., 1996).

Experiments in Asian countries have shown that application of organic amendments such as FYM (generally composted) and straw or green manure crops tends to build up SOM in all rice-based cropping systems (IRRI, 1986; Yadvinder-Singh et al., 1994; Singh and Paroda, 1994). Green manure with relatively high N and low C content, however, contributes less to SOM buildup than does straw or FYM. Rice soils in China are high in SOC, the consequence of hundreds of years of manuring (Table 4; Cheng, 1984).

B. Land Use Change and Soil Organic C Content

In a study of the influence of soil type and land use on SOM content, Van Noordwijk et al. (1995b) analyzed large soil data bases for the island of Sumatra (Indonesia). Based on their C contents, the soils were grouped into five classes: a) Histosols (peat); b) all wetland soils (classified as Aquic subgroups of various soil orders, previously classified as Gley soils); (c) Andisols (recent volcanic soils); d) a group of fairly fertile soils (Alfisols, Entisols, Inceptisols, Mollisols, and Spodosols; this group (very) roughly corresponds to the alluvial soils of earlier soil maps); and e) a group of acid soils of low fertility (Oxisols and Ultisols, including most of the previous Red Yellow Podzolics).

The Histosols, which cover 10% of Sumatra, probably contain more than 90% of all C stored in Sumatran soils. The Andisols and the wetland soils both contain about 100 g kg^{-1} of SOC. In the

Table 2. Soil organic C content in agricultural soils of selected Asia countries

Country	No. of samples	Mean	Standard deviation	Minimum	Maximum
		g kg^{-1}			
Tropical Asia	410	14.1	12.8	1.2	114.0
Bangladesh	53	11.8	8.3	4.7	60.0
Mayanmar	16	12.1	5.0	3.7	23.2
Cambodia	16	10.9	7.7	2.4	28.8
India	73	8.5	3.7	2.8	19.0
Indonesia	44	13.9	7.6	5.0	56.0
West Malaysia	41	33.6	25.3	6.0	114.0
Philippines	54	16.6	6.4	5.2	33.0
Sri Lanka	33	14.1	15.0	1.8	84.9
Thailand	80	10.5	6.7	1.2	29.5
Mediterranean Countries	62	18.2	14.5	3.5	86.0
Japan	84	33.3	20.2	10.0	113.6

(Adapted from Kyuma, 1988.)

Table 3. Effect of long-term fertilization and manuring on soil organic C for different cropping systems in India

Cropping system, location	Initial value	Control	Treatment NPK	NPK + FYM
	g kg^{-1}			
Rice–rice, Hyderabad	5.1	6.6	8.2	12.5
Rice–rice, Bhubaneswar	2.7	4.1	5.9	7.6
Rice–wheat-jute, Barrackpore	7.1	4.2	4.5	5.2
Rice–wheat–cowpea, Pantnagar	14.8	6.0	9.0	14.4
Maize–wheat–cowpea, Ludhiana	2.1	2.5	2.7	3.7
Maize–wheat, Palampur	7.9	6.2	8.3	12.0
Millet–cowpea–maize, Bangalore	5.5	3.4	4.5	4.8

(Adapted from Nambiar, 1994.)

Table 4. Effect of cropping system on organic matter content of paddy soils in South China

Location	Cropping system	Organic matter (g kg^{-1})
Hubei	Continuous rice	20.3 - 21.5
	Rice–dryland crops	18.5 - 19.4
Zhejiang	Continuous rice	31.1 - 52.1
	Rice–cotton	20.1 - 28.7
Taihu Lake Region	Rice–rice–wheat	27.4 ± 9.4
	Rice–wheat	24.5 ± 10.4
Shanghai suburbs	Rice–rice–wheat	21.4 ± 1.9
	Rice–wheat	15.8 ± 1.4

(Adapted from Cheng, 1984.)

Andisols, C is intimately bound to clay complexes; in wetland soils, C is partially protected from decomposition by anaerobic conditions. In the relatively fertile upland soils (Inceptisols) and Oxisols + Ultisols, SOC content is 38.0 g kg^{-1} and 32.0 g kg^{-1} respectively. The differences between all groups were statistically significant. Within the groups presented, no statistically significant differences between soil types were observed.

The wetland soils include human-made wet ricefields. The SOC content of these managed wetlands was below that of their natural counterparts in the sedge swamps. The widespread practice of burning rice straw at the end of the cropping cycle and the relatively young age of these wetlands may limit SOM accumulation compared with natural wetland vegetation.

In general, SOC content decreases in this order—primary forest, secondary forest, areas used for tree crops, and slash-and-burn series. In major upland soils, the difference in SOC content between land use types is about 5 g kg^{-1} C. At an average bulk density of 1.25 g cm^{-3}, this represents 10 Mg ha^{-1} for a 15-cm topsoil layer. Changes in deeper layers are likely to be smaller. In Andisols and wetland soils, larger differences in SOC content are observed between land use types, but the smaller number of observations makes comparison less certain. Potentially, land use effects on SOC may be more pronounced on these soils as management reduces the protection of SOC when Andisols are tilled and wetland soils are drained.

A comparison can be made with an analysis made in the 1930s of a large data set obtained by Hardon (1936) from Lampung on the southernmost corner of the island. Lampung's forest was then being transformed to agricultural land. For nearly all land use categories, Hardon's data fell within the more recent figures for Inceptisols and Oxisols plus Ultisols. Hardon's average topsoil content of SOC over all land uses (35.3 g kg^{-1}) is close to the present average of 34.6 g kg^{-1} for these soil groups. Van Noordwijk et al. (1995b) concluded that the average SOC content of the topsoil in Lampung/South Sumatra in the early 1930s was similar to the average for the whole of lowland Sumatra (excluding volcanic, wetland, and peat soil) in the late 1980s. There is no indication of any change in soil C storage under forests in the 50-year time span during which atmospheric CO_2 concentration increased by 20%.

C. Soil Properties and Soil Organic C Content

The data set of SOC for Sumatra in the 1980s confirms a relation between soil pH and SOC established in the 1930s by Hardon (1936). The combined data show that the lowest SOC content can be expected within pH range 5.0–6.0. Below pH 5.0, reduced biological activity may slow down the decomposition of organic matter. Most agricultural research recommends lime application at pH 5.0-6.0; this may stimulate breakdown of organic matter and thus contribute to crop nutrition, but possibly at the cost of maintaining the SOM content.

In a multiple regression analysis, management factors such as land use and soil pH, as well as 'permanent' soil characteristics (texture, elevation, slope, and soil type) all contributed to explain variation in SOC content. Comparison of land use effects can be easily confounded by differences in the more permanent soil attributes. Compared with average content per soil type and land use, the SOC content will decrease by 15% per unit increase in pH; increase by 1% and 0.7% per increase in clay and silt content, respectively; increase by 4% per 100-m increase in elevation; and decrease by 0.3% per percent increase in slope.

Thus SOC contents in the uplands of Sumatra are relatively higher (minimum 30 g kg^{-1}) than India's minimum of 3.0 g kg^{-1} (Tables 2, 3). The low values in India could probably be explained by the higher pH and lower clay content of the soils in the Indo-Gangetic Plains.

III. Annual C Budget for Different Cropping Systems

A. C Budget for Rice – Rice Systems

The C balance of a continuous irrigated rice system in the tropics (Cassman et al. 1995) was revised to include data for a N fertilizer treatment. Table 5 shows the large influence of N fertilizer on the amount and chemical composition of recycled crop residues. In a recent 2-year field study conducted at IRRI, applied N resulted in a 130% increase in aboveground dry matter while root and stubble dry matter increased by 38 and 75%, respectively (Table 5). Root dry matter and chemical composition were measured in samples taken at mid-grain-filling stage to assess quantity and quality of this source of C input. Stubble samples were taken just before incorporation in the subsequent crop cycle, again to best represent the characteristics of this C source. Applied N resulted in higher N and lower C concentration of roots, which reduced the C–N ratio by 30%. Stubble N concentration was also increased in plots receiving N fertilizer, although C concentration was similar with or without N fertilizer. The similarity in C concentration in the stubble may result from the decomposition of carbohydrates and other labile C substrates during the 2-month fallow period, when stubble remained in the field before incorporation.

The new C budget is based in part on actual measurements of C inputs and outputs in the annual triple-cropped rice system of the Long-Term Continuous Cropping Experiment at the IRRI research farm in the Philippines (Table 6). In this experiment, all aboveground biomass was removed at harvest of each crop so that only roots and basal portions of stems were recycled.

Two components of this budget were estimated with reasonable accuracy. First, SOC has remained constant over a 13-year period in both treatments with (22.4 g kg^{-1} SOC) and without applied N (19.6 g kg^{-1} SOC), indicating an equilibrium between C outputs and inputs (Cassman et al. 1995). Second, grain yields were measured in each crop cycle and this provided a reasonable estimate of aboveground biomass based on the tight conservation of harvest index (HI) in modern semidwarf rice varieties. The mean HI in this experiment was about 0.500 in the treatment without applied N and 0.475 in the N-fertilized treatment. Root dry matter as a proportion of total aboveground biomass and root C concentration also appear to be relatively stable within N fertilizer treatments (Table 5). The amount of C recycled with root and basal stems was therefore estimated as a proportion of total aboveground biomass and C concentration, and both were adjusted for the effects of applied N.

The other sources of C inputs were derived from published values. For example, C inputs from the algal community in floodwater were estimated in a field experiment at IRRI (Saito and Watanabe 1978), and estimates of a similar magnitude were made in irrigated rice crops at other locations (Yamagichi et al., 1980; Vaquer, 1984). In the revised C budget (Table 6), it was assumed that equivalent C inputs from aquatic photosynthetic biomass occurred in treatments with or without applied N because slower leaf area development and a more open canopy without applied N would offset the potential for increased growth of green algae stimulated by applied N. Although N broadcast into floodwater can cause algal blooms (Roger and Kurihara, 1991), decreased light penetration through a dense leaf canopy would reduce the potential productivity of the green algae. Also important to the C balance are differences in the chemical composition of floodwater biomass. Blue-green algae containing cyanobacteria that fix atmospheric N_2 dominate the soil–floodwater interface in plots without applied N, and these organisms have a relatively low C–N ratio (Simpson et al., 1994; Roger and Watanabe, 1986). In contrast, green algae would likely have a higher C-N ratio, which would affect C turnover rates from these inputs to irrigated rice systems. The C budget in Table 6 attempts to account for these differences.

There are no published reports on quantifying rhizodeposition in rice using ^{14}C, although many studies have been done on other crops, including wheat. Rhizodeposition of C from root turnover and exudates represented 5-20% of aboveground biomass in a greenhouse study with 11 plant species (Shamoot et al. 1968). Root exudates and turnover were therefore estimated to represent 15% of total

Table 5. Effect of N fertilizer application on shoot and root dry matter, and C and N content of root and stubble biomass in an irrigated lowland rice double-cropped system at the IRRI research farm in the Philippines. Values shown are the mean and standard error of the same treatment plots in 1994 and 1995 dry seasons (n = 8 for each value)

		Roots[b]				Stubble[c]			
Fert. N rate	Aboveground dry matter at maturity[a]	Dry matter	—Composition— C	N	C/N	Dry matter	—Composition— C	N	C/N
	kg ha^{-1}	kg ha^{-1}	g kg^{-1}	g kg^{-1}		kg ha^{-1}	g kg^{-1}	g kg^{-1}	
0	7530 ± 250	1420 ± 50	357 ± 3	4.9 ± 0.1	7351	2510 ± 120	313 ± 4	4.6 ± 0.1	68
190	17340 ± 370	1960 ± 45	330 ± 4	6.5 ± 0.2		4400 ± 110	305 ± 11	7.1 ± 0.1	43

[a] Aboveground dry matter was measured at physiological maturity.

[b] Root systems were sampled at mid-grainfilling stage and include the 1–2 cm basal portion of stems.

[c] Stubble was cut at 25-30 cm height and left standing in the field during a 2-week period after grain harvest until incorporation which precedes the subsequent wet season rice crop. Stubble was sampled immediately prior to incorporation.

Table 6. Estimated annual C balance in the long-term continuous cropping experiment at IRRI; three rice crops have been grown annually since 1968 in treatments without applied N (N_0) or with high rates of N fertilizer (N_f)

			Annual C balance							
	C/N ratio		Input (gross)		Turnover		Mineralization		Net input	
C source	N_0	N_f	N_0	N_f	N_0	N_f	N_0	N_f	N_0	N_f
			—kg ha^{-1}—		—%—		———g ha^{-1}———			
Aquatic photosynth. biomass	12	25	2100	2100	80	75	1680	1570	420	530
Rice root biomass	72	50	1070[a]	1290[a]	60	65	640	840	430	450
Root exudates and fine root turnover[b]	36	25	840	1390	70	75	590	1040	250	350
Soil organic matter[c]	10	10	---	---	4.3^{+}	4.9^{+}	1100	1330	-1100	-1330
Totals			4010	4780			4010	4780	0	0

[a] Assumes maximum root biomass is 19% and 14% of total aboveground biomass at maturity in N_0N_f treatments, respectively, with 36% C (N_0) or 33% (N_f) based on data provided in Table 5.

[b] Assumes that root exudates and turnover represent 15% of total aboveground biomass at maturity, with a C concentration of 36 and 33% in N_0 and N_f treatments, respectively.

[c] Total soil organic C in the 0–20 cm puddled soil layer was 25,500 and 27,000 kg ha^{-1} in the N_0 and N_f treatments, respectively, and remained constant in a 13-yr period from 1978 to 1991.

aboveground biomass at maturity with a C-N ratio that was sensitive to plant N supply (Table 6). The mean C-N ratio of the root turnover and exudate pool was assigned a value lower than that of the whole root system sampled during grain filling, and the decrease in C-N ratio of this pool in N-fertilized plants was assumed to be proportional to the change in C-N ratio of roots from treatments with and without applied N (Table 5).

Although there is considerable uncertainty in estimates of C inputs and turnover from aquatic biomass and root exudates, the other two components of the C budget in triple-cropped rice systems are based on direct measurements of SOC and plant biomass accumulation. Despite the uncertainty, several features of the C balance are notable and would not be greatly affected by changes in assumptions used in constructing the budget. Of particular importance is the estimate of only 4-5% SOM turnover. This rate of annual turnover in the triple-cropped rice system appears to be remarkably low, given the optimal year-round conditions for biological activity which includes a mean temperature of 24-27 °C, adequate moisture, and intensive soil tillage operations three times each year. Changes in assumptions about C inputs and outputs from aquatic biomass, root turnover, and exudates would not have a large effect on this estimate of annual C mineralization.

The percent annual turnover rates may be low in part because they are calculated from high total SOC levels (19.6 to 22.4 g kg^{-1} SOC). The equilibrium soil C level is greater with increasing numbers of irrigated rice crops per year (e.g., Olk et al., 1996). When the triple-cropped system was begun in this field, soil C increased for several years until a new steady state was reached at a higher soil C level (Cassman et al., 1995). In other fields placed under intensified rice cropping, this increase was more pronounced when initial soil C was low (De Datta et al., 1988).

High soil C contents in irrigated lowland fields must be reconciled with studies of straw decomposition that find only slightly slower rates of decomposition under submerged versus aerated conditions (Neue, 1985). Results of straw incubations that last for weeks or even months may primarily reflect degradation of the more labile plant molecules, which dominate the composition of straw and can decompose quickly regardless of soil moisture status. More resistant plant molecules such as lignin probably contribute substantially to maintaining soil C, but incubations that would detect an effect of soil moisture on lignin degradation might have to last several years. Furthermore, straw has a lower concentration of lignin than do roots (M. Becker, unpublished data), and this is allowed to decompose in situ in the field. Thus, in long-term field experiments on the IRRI farm, phenolic subunits of lignin were found to have accumulated in SOM with increasing intensity of irrigated rice cropping (Olk et al., 1996).

High SOC contents occur in tropical irrigated lowland fields despite the large effect that temperature has in accelerating mineralization of crop residues (Jenkinson and Ayanaba, 1977) and soil C (Howard and Howard, 1993). At mean temperatures of nearly 30°C, which are typical of lowland paddy soils, moisture is of secondary importance in controlling the rate of soil C mineralization (Howard and Howard, 1993).

A second notable feature is that C inputs from sources other than vascular plants are a major component of the C balance in irrigated rice systems. The effects of applied N on the quantity, chemical composition, and turnover rates of C in photosynthetic algal communities is therefore a key element of the C budget. To date, research addressing these issues is insufficient to provide reliable estimates of inputs and outputs from this important component of the soil-floodwater system.

A third feature is that equilibrium soil C levels indicate only a 6% increase from long-term use of N fertilizer despite more than a twofold increase in grain yield and plant biomass. Although N fertilizer subsidies have large effects on all components of the C balance, the net effect is attenuated by opposing influences on individual components (Table 5). Applied N increases net primary productivity of the rice crop by 130%, but it decreases both the C concentration in recycled crop residues and the root-shoot dry matter ratio. The net increase in recycled C from root biomass in the N-fertilized treatment was only about 20% greater than that without N application (Table 6). Moreover, the decomposition rate of root residues from a N-fertilized rice crop would be greater than without the applied N because of a lower

C-N ratio, which would further reduce the cumulative C sequestration from the increased root biomass resulting from N application. The same offsetting trends would be anticipated in the C-N ratio and decomposition rate of the root turnover and exudate pool.

Therefore, soil C is conserved or even increases in intensive double- and triple-cropped irrigated rice systems in the lowland tropics, despite high temperatures and adequate soil moisture throughout the year and even if no organic amendments such as straw or manures are applied. We suspect that the ability to sequester C under conditions that would otherwise favor organic matter depletion results from the relatively slow rate of soil C mineralization and the large C inputs from nonvascular plants in the soil-floodwater ecosystem.

B. CH_4 Budget for Rice Systems

Methane (CH_4) is generated in the last step of the anaerobic degradation of SOM and inputs to ricefields such as straw, root, and root exudates. This final part of the reaction chain occurs by three possible biochemical reactions: (1) fermentation of methylated compounds such as acetate, (2) the reduction of CO_2 in molecular hydrogen, and, with lesser importance, (3) the reduction of CO_2 and formate (Conrad, 1989). Microbial production of CH_4 is restricted to strongly reduced environments of less than -200 mV, which is commonly found in flooded rice soils starting approximately 2 wk after flooding. However, the surface and the top layer of the soil (about 1-2 cm) and parts of the rhizosphere are generally aerobic, and thus consume (oxidize) CH_4.

Bacterial number remains relatively constant in the course of the rice-growing season, whereas production rate of CH_4 is characterized by pronounced seasonal variations. In previous investigations, CH_4 production rates exceeded emission rates by a factor of 2-4 (Wassmann et al., 1993), indicating an intensive consumption of CH_4. Methane is consumed by aerobic bacteria that use C1 compounds as the sole energy source. The immediate product of CH_4 in bacterial metabolism is methanol, which is oxidized via formaldehyde and formate to CO_2. The methanotrophs that could be isolated so far depend on the availability of O_2 which is limited in the topsoil and the rhizosphere. Since methanotrophic bacteria can also oxidize ammonia, CH_4 oxidation is closely linked to the N cycle. Methane consumption can be reduced by high concentration of ammonia, e.g., after fertilization (Conrad and Rothfus, 1991; Bronson and Mosier, 1994).

The CH_4 produced in flooded rice soil can transfer to the atmosphere by three different pathways: (1) diffusion in aqueous media, (2) emergence in the form of gas bubbles (ebullition), and (3) diffusion through the plant aerenchyma. The diffusive flux of CH_4 through the pore and floodwater is reduced by low solubility and CH_4 consumption in the topsoil. The ebullitive CH_4 flux represents the dominant pathway during pre-transplant flooding and the early stage of the growing season, whereas plant-mediated transport prevails in the latter stages of the season (Wassmann et al., 1996). Percolation can also be a sink for soil-borne CH_4, but this pathway is of minor importance for most puddled rice soils.

Data on CH_4 emission have accumulated in recent years through various efforts to improve regional and global estimates. Ricefields were identified as a substantial source of CH_4, but global estimates on source strength vary from 20 to 80 Tg yr^{-1} (Bachelet and Neue, 1993). Part of this divergence can be attributed to varying methodologies with different sampling frequencies as well as inconsistent definitions of rice ecosystems (Neue and Boonjawat, 1996). Furthermore, the extrapolation of locally obtained emission data is complicated by pronounced temporal and spatial variations of CH_4 emission. The spatial variation is affected by both inherent soil properties and cultural practice. Rice soils can be grouped into classes with high, moderate, and low CH_4 emission potential, although the controlling factors for this classification are not yet clear (Wassmann et al., 1996). These varying potentials for CH_4 production may be superseded by organic amendments, which lead to enhanced CH_4 rates irrespective of soil type. The local water regime strongly affects the magnitude of CH_4 flux from ricefields as well (Bronson et al., 1997a).

Table 7. Carbon and methane balance for 1992 WS and 1993 DS

	Annual	—C-input (gross)—		—C mineralization—	
Source of C	turnover	Urea plot	Rice straw plot	Urea plot	Rice straw plot
	(%)	kg C ha^{-1} y^{-1}			
Aboveground biomass	75	190 (stubbles)	4190 (stubbles + straw)	140	3140
Root biomass	60[a]	860[a]	860	520	520
Rhizodeposition	75[a]	930	930	700	700
Aquatic biomass	75[a]	1400[b]	1400	1050	1050
Soil organic C	4.8[a]		--	1330	1420
Total		3380	7380	3740	6830
CH_4 emission[c]		40	571	40	571
C input		1.2%	7.7%	--	--
C-mineralization		--	--	1.1%	8.4%
CH_4 production[d]		172	1339	172	1339
C-mineralization				4.6%	19.6%
CH_4emission/CH_4 production		23.3%	42.6%	23.3%	42.6%
CO_2 production[e]				3568	5491

[a] Cassman et al., 1995.

[b] Saito and Watanabe, 1978 (2 growing seasons, no fallow).

[c] Measured by automated chamber system, sum of dry and wet seasons (Bronson et al., 1997a).

[d] Measured *in vivo* with intact soil cores (0–15 cm) under N_2 (Bronson et al., 1997a).

[e] Calculated by the difference between C mineralization and CH_4 production.

The increasing CH_4 concentration in the atmosphere is believed to contribute to global warming. Therefore, the development of methods to reduce sources of CH_4 emissions, including rice cultivation, should be part of today's efforts to protect the earth's atmosphere and to avert possible climatic change (Rennenberg et al., 1992).

Fluxes and pool sizes of CH_4 were determined during two growing seasons (a dry and a wet season) on plots receiving different levels of organic input (Table 7) (Bronson et al., 1997a,b). Surface fluxes were measured using an automated closed chamber system. Production of CH_4 was measured weekly in intact cores of the 0–15 cm soil surface layer in the laboratory under N_2. Although some CH_4 production occurs below 15 cm, studies in our laboratory showed that 90% takes place in this top layer. There was some variation between wet and dry season, but total emission fluxes from plots receiving high organic inputs (27.8–29.3 g CH_4–Cm^{-2}) always exceeded those from the low-input plots (1.3–2.7 g CH_4-Cm^{-2}).

Several notable features of the C budget that include CH_4 emission and production (15 cm soil surface) are shown in Table 7. The proportion of CH_4 emission to C inputs was 1.2% in the urea plots and 7.7% in the plots that received 5.5 t dry straw (2 t C ha^{-1}) plus urea each season. The percentage of CH_4 production that was emitted varied from 23 to 43%, which indicates that the preponderance of CH_4 produced is oxidized before it escapes through the rice plants (Conrad and Rothfus, 1991). The final line of the budget in Table 7 provides an estimate of CO_2 production obtained by subtracting the measured CH_4 production from the total C mineralization. These estimates indicate that the preponderance of C mineralization in this double-cropped rice system is as CO_2, probably during the relatively dry fallow periods, and immediately after soil puddling before the flooded soil becomes reduced.

C. C Budget for Rice – Wheat Systems

A C budget was constructed for the long-term rice – rice – wheat triple cropping experiment in Bhairahawa, Nepal (Tables 8, 9). This experiment began in 1979 with transplanting of "early" rice, which was followed by transplanting of "normal" rice and wheat planting in the same year. There are nine treatments in this experiment, which include various combinations of N, P, and K fertilizer, as well as treatments with FYM and straw. Fifteen-year grain yield data on this site were reported by Regmi (1994), and from these, estimates of total biomass production, root biomass, and rhizodeposition were made.

The C budget was based on two treatments—nonfertilized control and recommended inorganic fertilizer rates of 100–13–25 ($N - P_2O_5 - K_2O$).

In this experiment, straw and grain were cut at ground level at the time of harvest. Root biomass C and rhizodeposition are, therefore, the only inputs. Since straw biomass was not available, a HI of 0.48 was used for fertilized and nonfertilized rice crops (Yoshida, 1981). Root weight was estimated by the relationship:

Root weight = 0.212 (Total dry matter) 0.936 (Yoshida, 1981)

Rice roots were assumed to be 36 and 33% C for nonfertilized and fertilized crops, respectively, as discussed above.

Keith et al. (1986) reported in a study with ^{14}C that rhizodeposition during the growing season of wheat was 30% of total C accumulated above ground. This value was used in constructing our C balance in wheat and is similar to values obtained from other reports (Lucas et al., 1977; Jenkinson and Rayner, 1977).

We assumed slightly higher turnover rates than in the triple rice system. The effect of having one aerated crop in the cycle was assumed to more than offset the fact that the aerobic phase is in the cool season.

Inputs of C in fertilized treatments were 3.5-fold greater than in nonfertilized controls (Tables 8, 9). SOC mineralization was estimated by subtracting the total net inputs from the net change in SOC. The bulk density of the soil at the beginning of the experiment is not known. It is assumed, therefore, to have remained relatively close to the present value of 1.5 g cm^{-3}. This is not entirely unreasonable, considering that the only organic inputs were the roots. SOC declined from a value of 10.3 g kg^{-1} (by weight) in 1979 to 7.3 and 8.8 g kg^{-1} in the control and nonfertilized plots, respectively, by 1993. This is in contrast to the triple-rice site at IRRI where SOC remained constant over time, with no straw or manure additions.

The total amount of SOC that was estimated to have mineralized during the three crop cycles was 0.74 and 0.96 t C ha^{-1} yr^{-1} for nonfertilized and fertilized plots, respectively (Tables 8, 9). These values are less than the corresponding values for the triple-rice crop C budget at IRRI. However, since SOC of the soils in Bhairahawa are much lower than at IRRI, soil mineralization in Nepal still represents 4.5–4.8% of the total SOC pool in the 15-cm surface. Mineralization of SOC would presumably be as CH_4 during the rice crop and as CO_2 during the wheat crops and fallow periods. Consumption of atmospheric CH_4 during the wheat phase of the rice – wheat pattern is a possibility, but data about this potential C input are lacking.

Table 8. Estimation of annual C balance in plots without fertilizer-N addition in the rice–rice–wheat long-term experiment in Bhairahawa, Nepal (based on 15 years yield data from Regmi, 1994)

Source of C	Rice crop 1	Rice crop 2	Wheat	Total gross input	Annual turnover	Annual mineralization	Total net input
	t C ha^{-1}	t C ha^{-1}	t C ha^{-1}	t C ha^{-1}	%	t C ha^{-1}	t C ha^{-1}
Roots	0.08	0.18	0.15	0.41	60	0.24	0.16
Rhizodeposition	0.07	0.15	0.21	0.43	70	0.30	0.13
Total	0.14	0.21	0.36	0.84	--	0.55	0.34
Net change in soil organic C[a]	--	--	--	--		--	−0.45
Soil C-mineralization[b]	--	--	--	--	4.5	--	−0.74

[a] Based on total soil C (g kg^{-1}) in 0-15 cm topsoil at the beginning and end of 15 years. Bulk density (original value not known) is assumed to have remained constant at its present value of 1.5 g cm^{-3}.
[b] Total is calculated by difference (net change in soil organic C − total net inputs). Turnover rate is this number divided by C stock in 0–15 dm soil after 15 years (16.4 t C ha^{-1}).

Table 9. Estimation of annual C balance in plots with NPK fertilizer (100–13–25) addition in the rice–rice–wheat long-term experiment in Bhairahawa, Nepal (based on 15 years yield data from Regmi, 1994)

Source of C	Rice crop 1	Rice crop 2	Wheat	Total gross input	Annual turnover	Annual mineralization	Total net input
	t C ha^{-1}	t C ha^{-1}	t C ha^{-1}	t C ha^{-1}	%	t C ha^{-1}	t C ha^{-1}
Roots	0.39	0.40	0.60	1.39	70	0.97	0.42
Rhizodeposition	0.38	0.39	0.85	1.62	80	1.29	0.32
Total	0.77	0.78	1.45	3.00	--	2.27	0.74
Net change in soil organic C[a]	--	--	--	--		--	−0.23
Soil C-mineralization[b]	--	--	--	--	4.9	--	−0.96

[a] Based on total soil C (g kg^{-1}) in 0–15 cm topsoil at the beginning and end of 15 years. Bulk density (original value not known) is assumed to have remained constant at its present value of 1.5 g cm^{-3}.
[b] total is calculated by difference (net change in soil organic C − total net inputs). Turnover rate is this number divided by C stock in 0–15 dm soil after 15 years (19.8 t C ha^{-1}).

D. C Budget for Upland Systems

Table 10 gives estimates of the changes in total C stocks for an 8-year period of three benchmark areas in Sumatra. The Muara Tebo and North Lampung areas have lost substantial amounts of C to the atmosphere due to the conversion of logged-over and secondary forest. Rantau Pandan, on the other hand, has apparently sequestered C as its rubber agroforests matured.

Table 10. Estimated changes in total C balance of three benchmark areas of the "Alternatives to Slash and Burn Project" in Sumatra for the period 1986-1994, based on remote sensing data of land cover and average C contents of each land cover type

	Area (ha)	Total C loss (t)	total C gain (t)	Net C loss (t)	t C $ha^{-1}yr^{-1}$
Rantau Pandan	63,819	2,296,888	3,879,660	-1,583,712	-3.1
Muara Tebo	148,571	11,945,690	3,928,750	8,016,940	6.8
North Lampung	141,332	13,315,855	3,125,830	10,190,020	9.0

(Adapted from Van Noordwijk et al., 1995a,b.)

IV. Constraints to C Sequestration

A. Rice – Rice and Rice – Wheat Systems

Straw removal from rice and wheat fields in Asia is one of the biggest constraints to C sequestration. For example, most of the rice straw on 43 million ha of harvested riceland in India is removed and used for animal feed and bedding (Tanaka, 1978; Bhardwaj, 1995). In southeast and northeast Asia, rice straw is generally burned. As mentioned earlier, rice straw burning is becoming more common in northwest India, with the growing use of contracted combine harvesters. Rice straw contains large amounts of C and K and smaller amounts of N, P, and S, and its incorporation can lead to increased rice grain yields (Ponnamperuma, 1984). Bhardwaj (1995) estimates that 110 million t rice straw is available in India each year. This represents about 0.67 and 1.5 million t of N and K that could be recycled to the soil. However, farmers consider several factors other than soil fertility when evaluating ways to dispose of the straw; their decisions vary by site, depending on local economic and agronomic conditions (Flinn and Marciano, 1984). High labor costs and an increasing tendency to use relatively inexpensive inorganic fertilizers generally discourage farmers in East Asia from incorporating too much straw. Wheat straw is favored far more than rice straw for animal feed (Bhardwaj, 1995). For this reason, hand-harvesting of wheat in India remains the norm, although use of the combine for wheat is increasing somewhat.

In Asia, composting is an important way by which organic wastes are returned to the soil. Starting materials include animal dung, human waste, sewage sludge, and waste water. Typically, these starting materials are composted with straw either aerobically or anaerobically in pits or shelters for 16–32 wk. Inoculants that are used in research to speed up the decomposition process include *Trichurus spiralis*, *Paeciliomyces fusisporus*, *Trichoderma*, and *Aspergillus* sp. (Guar and Singh, 1995). Constraints to composting in Asia include time, labor, N volatilization losses, and nutrient imbalance in the starting materials. Human wastes, historically recycled at 90% rates in China (AIT, 1989), have the added disadvantage of carrying pathogens. Thermophilic composting may be required for up to 2 years to kill all the pathogens in human excreta. Earthworm maintenance is a constraint in vermi-composting.

Green manuring has been practiced in Asia for hundreds of years; its benefits to rice yields are summarized by Meelu and Morris (1988) and by Yadvinder-Singh et al. (1994). Typically, green manure crops are grown in Asia at the onset of the monsoon, when intermittent rains are sufficient to grow, for example, *Sesbania sesban*, but not rice. In rice – wheat rotations, the long-term benefit of green manuring each year before rice to the yield of the following wheat is small and usually not significant (Mann and Garrity, 1994). Constraints to green manuring include seed availability, lack of rain or irrigation, and high incorporation costs (Ali and Narciso, 1994). Economic studies conducted by IRRI showed that the short-term benefits of green manuring were negative in India and Nepal and positive in the Philippines. The amounts of C on a dry matter basis in 40 to 60-day-old green manure is smaller than what is usually added in manure or composts (Meelu and Morris, 1988).

A very important deterrent to the use of organic amendments is the wider availability and relatively low prices of fertilizer in Asia (Flinn and Marciano, 1984). A good example is China, where composting is still common, but declining. This trend coincides with an increase in average rate of NPK applied to rice from 248 kg ha^{-1} in 1980 to 446 kg ha^{-1} in 1990.

B. Upland Systems

One of the main constraints to C sequestration in the uplands of Asia is the permanent cropping that takes place on land that is more suitable to tree cropping. Other common practices that lead to land degradation and C losses include forest clearing with bulldozers and sugarcane cropping systems with burning practices.

Hairiah et al. (1995) were able to distinguish three groups of land use based on a recently developed size-density fractionation method for SOM (Meijboom et al., 1995): a) forest (remnants of logged-over primary and various types of secondary forest); b) SOM-maintaining practices: (woodlots, forest plantation, home garden, and unburned Imperata); and c) degrading land: burned *Imperata*, sugar cane plantation with burning practices, and forest plantation with land clearing by bulldozer.

Under SOM-maintaining practices without burning or removal of plant residues from the plot, the amount of C in all sand-sized fractions in the top 5 cm of the soil still decreased by about 20–30% from the forest level, even when the light fraction increased by about 40%. Under land-degrading situations, the data suggested a 70–80% decrease in the sum of sand-sized fractions 8-10 yr after opening the forest. In the 5–15 cm deep layer, however, the amount of C in the converted forest sites exceeded that in the forest. Total content of the sand-sized C fractions for this second layer is only 20-50% of that in the top 5 cm. In the 5-15 cm soil layer, the heavy fraction is dominant over the light and intermediate fraction in terms of dry weight and C content.

When corrected for soil type in the Sumatran data set, the difference between the C stocks in soils under different land uses is smaller than what is generally assumed (< 5.0 g kg^{-1} SOC). Differences in aboveground C storage are much larger than those in soil C stocks. Research concerned with global C budgets and effects of land use change on C emission must focus on the peat and wetland soils; drainage of a small percentage of the Histosols may release more CO_2 into the atmosphere from current soil sources than transformation of all remaining forest into Imperata grasslands.

Prospects for C sequestration in the soil in upland cereal or upland rice cropping by modifying management practices to include organic amendments, for example, appear small, but these are still regionally and globally very important. In China and India, straw or green manure amendments improved SOC contents by 1.0 and 3.0 g kg^{-1}, after 4 and 10 yr of application, respectively (Singh and Paroda, 1994). This translates to an increase (considering a measured 6% drop in bulk density) in SOC in the 0–15 cm surface soil of 1.4 and 4.2 t C ha^{-1}, respectively, sequestered in the soil. An equivalent incorporation of green manure and straw on the 35 million ha of irrigated rice and 147 million ha of rice – wheat land in South and Southeast Asia would result in a sequestration of 147 million t C. This does not include the extra atmospheric CO_2 fixed in the crop biomass as a result of higher productivity of rice and wheat. If annual grain yields were to increase by 1 t ha^{-1} with higher SOM, an additional 28 million t C would be sequestered.

V. Soil Organic Matter and Productivity

A. Rice – Rice and Rice – Wheat Systems

In double- and triple-cropped rice systems, SOM is an important storehouse of nutrients, N, P, and S. As the most commonly limiting nutrient, N uptake is often a key factor in cereal crop productivity. Nitrogen taken up by a crop can be considered as being derived either from SOM or directly from applied fertilizer (Appel, 1994; Cassman et al., 1996b). Several studies at IRRI showed that mineralization of soil organic N contributed 40–60% of total N taken up by irrigated rice when estimated by ^{15}N or by the N difference between N-fertilized and nonfertilized plots (although the amount of soil N uptake by rice can be as low as 20% at high N fertilizer rates). Determining a fertilizer schedule for optimal use efficiency of applied N fertilizer is therefore predicated on knowledge of the rate of SOM-N mineralization.

Total soil N would seem related to SOM-N mineralization, and this has indeed been proposed as an index of annual release of N (Neue, 1985). Recent on-farm studies have, however, found weak and statistically nonsignificant correlation between total soil organic N and indigenous soil N supply (defined as the N uptake by irrigated rice in check plots receiving no fertilizer N) (Cassman et al., 1996a). This finding of no correlation was repeated at five sites, each having minus N fertilizer check plots in 24–36 farmers' fields in one of five Asian nations (Cassman et al., unpublished data). Within each site, the indigenous soil N supply varied greatly between neighboring farmers' fields (Stalin et al., 1996).

Additionally, it was found that building up SOM through years of manuring does not necessarily translate into higher N mineralization rates in rice (Cassman et al., 1996c). This was attributed to two factors. First, although N mineralization was higher in plots subjected to green manuring during the transition from aerobic to anaerobic soil conditions after puddling and transplanting, there is a period of about 14–21 d when crop N demand is small. For the remainder of the crop growth period, N mineralization was similar to control plots that received only N fertilizer. Second, abiotic immobilization of N may occur due to the aromatic structure of the humus that accumulated in the continuously flooded conditions of double- and triple-cropped irrigated rice systems (Olk et al., 1996). Thus, the quality of SOM changes despite increasing levels of total SOC and N. In contrast, strong positive correlations between SOM content and N mineralization are assumed in strictly upland conditions.

Increasing SOM with continual manuring does not therefore appear to have as much benefit for nutrient supply in rice as was previously thought. Water-holding capacity does improve in rice soils with higher SOM levels brought about by long-term straw incorporation as compared with straw removal (26.8 vs 25% water-holding capacity) (Sidhu and Beri, 1989). Although rice soils are generally puddled, improving water ~~relations in the soil by SOM accumulation would be beneficial in coarse-textured soils,~~ in soils that do not form hardpans, and in rainfed areas.

Soil physical properties are more important in the wheat phase of the rice – wheat cropping system than in the puddled rice culture. This is because of difficulties in seedling establishment in heavy-textured soils and because wheat, unlike rice, is a deep-rooted crop. These physical properties include decreased bulk density, improved water infiltration rates, and improved soil structure (Verma and Bhagat, 1992), all of which can result from SOM buildup. Improved water-holding capacity by building up SOM would also be important in dry-seeded rice, which is becoming popular in Asia as labor costs for transplanting increase and as water becomes scarce. The relation between SOM content and N supply in wheat grown in the subtropics of South Asia in rice - wheat rotation is currently being studied by IRRI scientists.

As mentioned earlier, there is ample agronomic evidence to indicate that green manure crops boost yields of the subsequent monsoonal rice (Yadvinder-Singh et al., 1994). But caution must be taken in interpreting these results because the purely inorganic fertilizer plots do not usually receive extra fertilizer corresponding to the nutrient content of the green manure. The economics of green manuring is another question altogether and is generally not favorable (Ali and Narciso, 1994).

Benefits to all crops in multiple-cropping systems are more apparent when compost or FYM or cow dung is applied at typical rates of 10 t ha^{-1}. Compost usually contains N, P, and K levels equivalent to 1 to 1.5% N, P_2O_5, and K_2O. Nambiar (1994) reported yield benefits for all crops in rice-based long-term experiments where FYM plus recommended NPK treatments were compared with NPK alone. Again, it should be noted that these comparisons are not based on equivalent nutrient application rates. In the case where a yield decline is evident, for example, in the rice phase of the long-term rice – wheat – cowpea experiment in Pantnagar, India, rice yields are higher with FYM + NPK compared with NPK, but the rate of yield decline is the same. In the Broadbalk long-term wheat experiment in the UK, on the other hand, addition of 35 t FYM ha^{-1} did not result in yields higher those than achieved with inorganic fertilizers alone (Jenkinson, 1991).

The high C–N ratio of straw complicates its management. Fresh straw incorporation can lead to immobilization of a sizeable amount of inorganic N in the soil before net N mineralization occurs. Timing the straw incorporation as soon as possible after harvest to maximize decomposition time before the next crop is beneficial (Tanaka, 1978), but not always practical. Applying small doses of "starter N" to aid straw breakdown is another solution. Interseeding green manure into flowering wheat can prevent yield depression in the following rice crop with wheat straw incorporation (Meelu et al., 1990). The possibility of increased CH_4 from the wheat straw in this system would have to be evaluated.

Rice and grain yields in northwest India are the highest in South Asia, despite the country's low SOM levels (4.0 g kg^{-1} organic C is typical) and widespread burning of straw. Although average wheat yields are still increasing, rice yields have been stagnant in Punjab and Haryana states since the late 1970s. There is strong evidence that factor (i.e., fertilizer) productivity in rice has begun to decline in this region (Chaudhary and Harrington, 1993). There is a current consensus to limit straw burning in Punjab and Haryana states because of the worsening air pollution during rice harvest season. In the face of all these, farmers will be forced to manage their residues differently. If crop management practices that prevent yield depression (sometimes associated with straw incorporation) are used, recycling of straw in rice-based cropping systems would lead to higher SOM levels. Consequently, higher productivity with reduced N inputs can be achieved than when straw is removed or burned (IRRI, 1989; Beri et al., 1995; Cassman et al., 1996c).

The low SOM situation in the Indo-Gangetic Plains in India constrasts with that existing in multiple rice systems of Southeast Asia. However, the impact of changes in SOM quality in continuously irrigated double- and triple-cropped systems and their effects on C and N mineralization must be evaluated. Perhaps it is not possible to maintain soil N supply capacity and SOC levels in rice – rice cropping without a periodic break for an upland crop (Cassman, 1995; 1996a). The rice – wheat system has an aerated soil cropping cycle, and although it occurs in the cool season, it appears to cause a decline in SOC levels unless straw is returned and manure is applied.

The situation in China differs from that in India or Southeast Asia. Fertilizer application rates are among the highest in the world and use of organic manure is still relatively common, though in decline. Grain yields are high, especially for rice, but there is evidence of emerging productivity (Byerlee, 1992). Environmental concerns, however, are coming to the forefront in Chinese agriculture. The problems of nitrate contamination of groundwater (Singh and Paroda, 1994) and high emission rates of greenhouse gases such as CH_4 and N_2O are directly related to excessive nutrient application.

B. Upland Systems

Soil organic matter in upland soils has direct and indirect roles in nutrient supply (Woomer and Swift, 1994; Buresh, 1995). A balance is needed between short-term gains from SOM mineralization and its stabilization into fractions which help to maintain soil structure (Kooistra and Van Noordwijk, 1995) and detoxify aluminum and other metals. Research efforts to quantify the degree of synchrony (Woomer and Swift, 1994) between nutrient release from mineralization and crop demand, and hence increased nutrient use efficiency of cropping systems, did not have substantial practical impacts (Myers et al., 1996), probably because most of the techniques for modifying time and place of mineralization require more labor or result in reduced flexibility in the choice of crops (Table 11).

Evidence is accumulating to show that upland and forest soils may consume (oxidize) substantial amounts of CH_4, depending on land use. Preliminary measurements in Sumatra suggest that agroforests and other land use systems which maintain a surface litter layer may be as effective in removing CH_4 from the atmosphere as do forest soils, while currently cropped and degraded lands have lost most of this capacity or act as (moderate) CH_4 sources (Van Noordwijk et al., 1995b).

Table 11. Farmer management options to improve synchrony of nutrient mineralization of organic inputs and crop demand

Management options	Drawback / constraint
Quality of organic inputs	
Choice of species, especially if a cover crop/green manure	Direct economic value usually dominates choice of species; potential conflict where there is more than one use
Management of plants grown as green manure	Low N gives less and slowly decomposing litter
Mixing organic sources in combination with mulch/manure transfer	High labor requirements
Location of organic inputs	
Placement, e.g., surface-applied vs. incorporated, flat vs. ridged, band placement	Erosion risks of tillage; volatilization losses from surface mulch
In situ mulch production intercropping or sequential systems	Competition in simultaneous systems
Mulch/manure transfer	High labor requirements
Timing	
Adjusting crop species to existing mineralization pattern	Reduced choice of crop species
Timing of organic and inorganic inputs	Labor requirements; crop growth cycle; knowledge and lack of predictability

(Adapted from Myers et al., 1996.)

VI. Summary and Conclusions

Asia has 1,259 million ha of agricultural land: 425 million ha are arable land, 34 million ha are devoted to permanent crops, and 800 million ha are permanent pasture. Rice farming is the most important land use of arable land (132 million ha). Carbon levels in the lowland rice soils of tropical and subtropical Asia generally remain constant, despite straw removal in the low-producing rainfed regions and burning of straw in the more productive, irrigated rice areas. Methane emissions are an important feature of the C cycle in rice soils, with emissions of CH_4 from ricefields in Asia currently estimated at about 63 Tg yr^{-1}. In the 12 million ha belt of rice – wheat cropping in South Asia, SOC is declining or is at low equilibrium levels. The constraints to returning straw to rice and wheat fields in Asia are formidable. In clayey, acid upland soils, C stocks are generally higher than in the rice – rice and rice – wheat soils of South and Southeast Asia. Agroforestry systems are effective in sequestering SOC, compared with continuous sugarcane cropping with burning. The role of SOM in raising the productivity of rice – wheat systems is likely related to improved soil physical properties and N supply. In the intensive, irrigated rice soils of Southeast Asia, soil physical properties are less important, and building up SOM levels appears to have no long-term benefit to N supply–capacity of the soil.

References

Abrol, I.P. and M.S. Gill. 1994. Sustainability of Rice-Wheat Systems in India. p. 172-183. In: Sustainability of Rice-Wheat Production Systems in Asia. R.S. Paroda, T. Woodhead, and R.B. Singh (eds.), Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific, Bangkok, Thailand.

AIT. 1989. Reuse of Wastes. ENFO News, II (4), 6, 10.

Ali, M. and J.H. Narciso. 1994. Economic evaluation and farmers' perception of green manure use in rice-based farming systems. p. 173-194. In: J.K. Ladha and D.P. Garrity (eds.). *Green Manure Production Systems for Asian Ricelands.* Selected papers from the International Rice Research Conference. International Rice Research Institute, Los Banos, Philippines.

Appel, T. 1994. Relevance of soil N mineralization, total N demand of crops and efficiency of applied N for fertilizer recommendations for cereals–Theory and application. *Zeitschrift fur Pflanzenernahrung und Bodenkunde* 157:407-414.

Bachelet, D. and H.U. Neue. 1993. Methane emissions from wetland rice area of Asia. *Chemosphere* 26(1-4):219-237.

Bhardwaj, K.KR. 1995. Recycling of crop residues, oil cakes, and other plant products in agriculture. p. 9-30. In: H.L.S. Tandon (ed.), *Recycling of Crop, Animal, Human, and Industrial Wastes in Agriculture.* Fertiliser Development and Consultation Organization. New Delhi.

Beri, V., B.S. Sidhu, G.S. Bahl, and A.K. Bhat. 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.

Bronson, K.F. and A.R. Mosier. 1994. Suppression of methane oxidation in soil by nitrogen fertilizers, nitrification inhibitors, and urease inhibitors. *Biol. Fertil. Soils* 17:263-268.

Bronson, K.F., H.U. Neue, U. Singh, and E.B. Abao, Jr. 1997a. Automated chamber measurements of CH_4 and N_2O in a flooded rice soil. I. Effect of organic amendments, nitrogen source, and water management. *Soil Sci. Soc. Am. J.* 61: (in press.)

Bronson, K.F., U. Singh, H.U. Neue, and E.B. Abao, Jr. 1997b. Automated chamber measurements of CH_4 and N_2O in a flooded rice soil. II. Fallow period emissions. *Soil Sci. Soc. Am. J.* 61: (in press.)

Buresh, R.J. 1995. Nutrient cycling and nutrient supply in agroforestry systems. p 155-164 In: R. Dudal and R.N. Roy (eds.), *Integrated Plant Nutrient Systems.* FAO, Rome

Byerlee, D. 1992. Technical change, productivity, and sustainability in irrigated cropping systems of South Asia: Emerging Issues. *J. Internation. Dev.* 4:477-496.

Cassman, K.G., S.K. De Datta, D.C. Olk, J.M. Alcantara, M.I. Samson, J.P. Descalsota, and M.A. Dizon. 1995. Yield decline and the nitrogen economy of long-term experiments on continuous, irrigated rice systems in the tropics. p. 181-222. In: R. Lal and B.A. Stewart (eds.), *Soil Management: Experimental Basis for Sustainability and Environmental Quality.* Lewis/CRC Publishers, Boca Raton, FL.

Cassman, K.G. and P.L. Pingali. 1995. Intensification of irrigated rice systems: Learning from the past to meet future challenges. *GeoJournal* 35:299-305.

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

Cassman, K.G., G.C. Gines, M.A. Dizon, M.I. Samson, and J.M. Alcantara. 1996b. Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen. *Field Crops Research* 47:1-12..

Cassman, K.G., S.K. De Datta, S.T. Amarante, S. Liboon, M.I. Samson, and M.A. Dizon. 1996c. Long-term comparison of the agronomic efficiency and residual benefits of organic and inorganic nitrogen sources for lowland rice in the tropics. *Experimental Agric.* 32:427-444.

Chaudhary M.K., and L.W. Harrington. 1993. The Rice-Wheat System in Haryna: Input-Output Trends and Sources of Future Productivity Growth. Mexico, D.F.: C.C.S. Haryana Agricultural University Regional Reseach Station (Karnal) and CIMMYT.

Cheng, Yun-sheng. 1984. Effects of drainage on the characteristics of paddy soils in China. p. 417-430. In: *Organic Matter and Rice*. International Rice Research Institute, Los Banos, Philippines.

Conrad, R. 1989. Control of methane production in terrestrial ecosystems. p. 39-58. In: M.O. Andreae and D.S. Schime (eds.), *Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere.* Dahlem Konferenzen. Wiley, Chichester.

Conrad, R. and F. Rothfuss. 1991. Methane oxidation in the soil surface layer of a flooded rice field and the effect of ammonium. *Biol. Fertil. Soils* 12:28-32.

De Datta, S.K., K.A. Gomez, and J.P. Descalsota. 1988. Changes in yield response to major nutrients and in soil fertility under intensive rice cropping. *Soil Sci.* 146:350-358.

FAO. 1996. Agrostat.

Flinn, J.C. and V.P. Marciano. 1984. Rice straw and stubble management. p. 593-611. In: *Organic Matter and Rice*. International Rice Research Institute, Los Banos, Laguna, Philippines.

Garrity, D.P., D.M. Kummer, and E.S. Guiang. 1993. The Philippines. p. 549-624. In: *Sustainable Agriculture and the Environment in the Humid Tropics*. National Academy Press. Washington D.C.

Guar, A.C. and G. Singh. 1995. Recycling of Urban and Rural Wastes Through Conventional and Vermi-Composting. p. 31-49. In: H.L.S. Tandon (ed.), *Recycling of Crop, Animal, Human, and Industrial Wastes in Agriculture.* Fertiliser Development and Consultation Organization. New Delhi.

Hairiah, K., G. Cadisch, M. van Noordwijk, A.R. Latief, G. Mahabharata, Syekhfani. 1995. Size-density and isotopic fractionation of soil organic matter after forest conversion. In: A. Schulte and D. Ruhiyat (eds.), Proc. Balikpapan Conf. on Forest Soils Vol. 2:70-87

Hardon, H.J. 1936. Factoren, die het organische stof-en het stikstof-gehalte van tropische gronden beheerschen (Factors controlling the organic matter and the nitrogen content of tropical soils). *Landbouw XI* (12):517-540.

Hobbs, P.R., G.P. Hettel, R.K. Singh, R.P. Singh, L.W. Harrington, V.P. Singh, and K.G. Pillai (eds.). 1992. Rice-Wheat Cropping Systems in Faizabad District of Uttar Pradesh, India: Exploratory Surveys of Farmers' Practices and Problems and Needs for Further Research. Mexico, D.F. CIMMYT.

Howard, D.M. and P.J.A. Howard. 1993. Relationships between CO2 evolution, moisture content and temperature for a range of soil types. *Soil Biology and Biochemistry* 25:1537-1546.

IRRI. 1967. Annual Report, International Rice Research Institute, Los Banos, Philippines.

IRRI. 1986. Annual Report, International Rice Research Institute, Los Banos, Philippines.

IRRI. 1989. Annual Report, International Rice Research Institute, Los Banos, Philippines.

IRRI. 1991. World rice statistics. 1990. International Rice Research Institute, Los Banos, Philippines.

IRRI. 1995. World rice statistics. 1993-1995. International Rice Research Institute, Los Banos, Philippines.

IRRI. 1993. 1993-1995 IRRI Rice Almanac International Rice Research Institute, Los Banos, Philippines.

Jenkinson, D.S. and J.H. Rayner. 1977. The turnover of soil organic matter in some of the Rothamstead Classical Experiments. *Soil Sci. 123:298-305.*

Jenkinson, D.S. and A. Ayanaba. 1977. Decomposition of carbon-14 labeled plant material under tropical conditions. *Soil Sci. Soc. Amer. J.* 41:912-915.

Jenkinson, D.S. 1991. The Rothamstead long-term experiments: Are they still of use? *Agron. J.* 83:2-10.

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

Kooistra, M.J. and M. Van Noordwijk., 1995. Soil architecture and distribution of organic carbon. p. 15-57. In: M.R. Carter and B.A Stewart (eds.), *Structure and Organic Carbon Storage in Agricultural Soils.* Advances in Soil Science, CRC Lewis Publ., Boca Raton, FL.

Kyuma, K. 1988. Paddy soils of Japan in comparison with those in Tropical Asia. p. 5-19. In: Proceedings, First International Symposium on Paddy Soil Fertility, Chiangmai, Thailand 6-13 December, 1988.

Lianzheng, W. and G. Yixian. 1994. Rice-wheat systems and their Development in China. p. 160-171. In: R.S. Paroda, T. Woodhead, and R.B. Singh (eds.), *Sustainability of Rice-Wheat Production Systems in Asia.* Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific, Bangkok, Thailand.

Lucas, R.E., J.B. Holtman, and L.J. Connor. 1977. Soil carbon dynamics and cropping practices. p. 333-351 In: W. Lockertz (ed.), *Agriculture and Energy.* Academic Press, London.

Mann, R.A. and D.P. Garrity. 1994. Green manures in rice wheat cropping systems in Asia. p. 27-42. In: J.K. Ladha and D.P. Garrity (eds.,) *Green Manure Production Systems for Asian Ricelands.* Selected papers from the International Rice Research Conference. International Rice Research Institute, Los Banos, Philippines.

Meelu, O.P. and R.A. Morris. 1988. Green manure management in rice-based cropping systems. p. 209-222. In: Green Manuring in Rice Farming. International Rice Research Institute, Los Banos, Philippines.

Meelu, O.P., Yadvinde-Singh, and Bijay-Singh. 1990. Green manure and crop residue management in wetland rice production. p. 734-735. In: 14th International Congress of Soil Science. Transactions Kyoto, Japan, Vol. IV.

Meijboom, F.W., J. Hassink, and J. Van Noordwijk. 1995. Density fractionation of soil macroorganic matter using silica suspensions. *Soil Biol. Biochem.* 27:1109-1111.

Myers R.J.K., M. Van Noordwijk, and P. Vityakon. 1996. Synchrony of nutrient release and plant demand: plant litter quality, soil environment and farmer management options. In: G. Cadisch and K.E. Giller (eds.), *Plant Litter Quality and Decomposition.* CABI, Wallingford (in press).

Nambiar, K.K.M. 1994. Soil Fertility and Crop Productivity under Long-term Fertilizer Use in India. Indian Council for Agricultural Research, New Delhi.

Nambiar, K.K.M. 1995. Major Cropping Systems in India. p. 135-142. In: V. Barnett, R. Payne, and R. Steiner (eds.). *Agricultural Sustainability: Economic, Environmental and Statistical Considerations.* John Wiley & Sons Ltd. Chichester.

Neue, H.U. and J. Boonjawat. 1996. Methane emission from ricefields. In: J. Galloway and J. Melillo (eds.), *Asian Change in the Context of Global Change.* IGBP Book Series. Cambridge University Press (in press).

Neue, H.U. 1985. Organic matter dynamics in wetland soils. p. 109-122. In: *Wetland Soils: Characterization, Classification, and Utilization.* International Rice Research Institute, Los Banos, Laguna, Philippines.

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

Ponnamperuma, F.N. 1984. Straw as source of nutrients for wetland rice. p. 117-136. In: *Organic Matter and Rice.* International Rice Research Institute, Los Banos, Laguna, Philippines.

Ponnamperuma, F.N. 1972. The chemistry of submerged soils. *Adv. Agron.* 24:29-96.

Roger P. A. and Y. Kurihara. 1991. The floodwater biology of tropical wetland rice fields. p. 211-233. In: *Soil Management for Sustainable Rice Production in the Tropics.* (IBSRAM monograph No.2), International Board for Soil Research and Management, Bangkok.

Roger P.A. and I. Watanabe. 1986. Technologies for utilizing biological nitrogen fixation in wetland rice: potentialities, current usage, and limiting factors. *Fertilizer Res.* 9:39-77.

Regmi, A.P. 1994. Long-term effects of organic amendment and mineral fertilizers on soil fertility in a rice-rice-wheat cropping system in Nepal. M.S. Thesis, University of the Philippines at Los Banos.

Rennenberg, H., R. Wassmann, H. Papen, and W. Seiler. 1992. Trace gas exchange in rice cultivation. *Ecol. Bull.* (Copenhagen) 42:164-173.

Saito, M, and I. Watanabe. 1978. Organic matter production in rice field floodwater. *Soil Sci. Plant Nutrition* 24:427-440.

Shamoot, S., L. McDonald, and W.V. Bartholomew. 1968. Rhizo-deposition of organic debris in soil. *Soil Sci. Soc. Amer. Proc.* 32:817-820.

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

Singh, R.B. and R.S. Paroda. 1994. Sustainability and productivity of rice-wheat systems in the Asia-Pacific Region: Research and Technology Development Needs. p. 1-35. In: R.S. Paroda, T. Woodhead, and R.B. Singh (eds.), *Sustainability of Rice-Wheat Production Systems in Asia.* Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific, Bangkok, Thailand.

Simpson, I.C., P.A. Roger, R. Oficial, and I.F. Grant. 1994. A study of the effects of nitrogen fertilizer and pesticide management on floodwater ecology in a wetland ricefield: I. Experimental design and dynamics of the photosynthetic aquatic biomass. *Biol. Fertil. Soils* 17:129-137.

Stalin, P., K.G. Cassman, A. Dobermann, T.M. Thiyagarajan, and H.F.M. ten Berge. 1996. Measuring nitrogen supplying capacity of irrigated rice soils. *Commun. Soil Sci. Plant Anal.* (in press).

Tanaka, A. 1978. Role of organic matter. p. 605-620. In: *Soils and Rice.* International Rice Research Institute, Los Banos, Philippines.

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

Wassmann, R., H. Papen, H. Rennenberg. 1993. Methane emission from rice paddies and possible mitigation options. *Chemosphere* 26:201-217.

Wassmann, R., H.U. Neue, M.C.R. Alberto, R.S. Lantin, C. Bueno, D. Llenaaresas, J.R.M. Arah, H. Papen, W. Seiler, and H. Rennenberg. 1996. Fluxes and pools of methane in wetland rice soils with varying organic inputs. *Environ. Monitoring Assess.* 42:163-173.

Woodhead, T., R. Huke, and E. Huke. 1994. Areas, locations, and ongoing collaborative research for the rice-wheat systems of Asia. p. 126-130. In: R.S. Paroda, T. Woodhead, and R.B. Singh (eds.), *Sustainability of Rice-Wheat Production Systems in Asia.* Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific, Bangkok, Thailand.

Vaquer, A. 1984. La production algae dans les rizieres de Carargue pendant la periode de submersion. Ver Internat. *Verein. Limnol.* 22:1651-1654.

Van Noordwijk, M., T.P. Tomich, R. Winahyu, D. Murdiyarso, S. Partoharjono, and A.M. Fagi (eds.). 1995a. Alternatives to Slash-and-Burn in Indonesia, Summary Report of Phase 1. ASB-Indonesia Report Number 4, Bogor, Indonesia

Van Noordwijk, M., D. Murdiyarso, U. Rosalyna-Wasrin, K. Hairiah, and A. Rachman. 1995b. Soil aspects of the Indonesian benchmark area of the global project on alternatives to slash and burn. p. 33-69. In: A. Schulte and D. Ruhiyat (eds.), Proc. Balikpapan Conference on Forest Soils, Vol. 2.

Verma, T.S. and R.M. Bhagat. 1992. Impact of rice straw management practices on yield, nitrogen uptake and soil properties in wheat-rice rotation in northern India. *Fert. Res.* 33:97-106.

Woomer, P.L. and M.J. Swift. (eds.). 1994. *The Biological Management of Tropical Soil Fertility.* John Wiley and Sons, Chichester, U.K., 243 pp.

Yamagichi, T., K. Okada, and Y. Murata. 1980. Cycling of carbon in a paddy field. *Jpn. J. Crop Sci.* 49:135-145.

Yadvinder-Singh, J.K. Ladha, Bijay-Singh, and C.S. Khind. 1994. Management of nutrient yields in green manure systems. p. 125-123. In: J.K. Ladha and D.P. Garrity (eds.), *Green Manure Production Systems for Asian Ricelands*. Selected papers from the International Rice Research Conference. International Rice Research Institute, Los Banos, Philippines.

Yoshida, S. 1981. *Fundamentals of Rice Crop Science*. International Rice Research Institute, Los Banos, ines.