ORGANIC MATTER ACCUMULATION IN SUBMERGED SOILS

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The decomposition and accumulation of organic materials in submerged (anaerobic) soils and sediments differ considerably from those in their aerobic counterparts. This is caused by the lack of oxygen or anaerobiosis. Compared to aerobic soils, there is preferential accumulation of organic matter in submerged rice soils. This paper reviews the current literature to establish basis or bases for organic matter accumulation in wetland soils and sediments. The decomposition or destruction of organic materials is lessened and incomplete, and the humification of organic matter is decreased under flooded conditions. Consequently, the overall organic matter decomposition rates are slower in submerged soils than those in aerobic soils and this results in net accumulation of organic matter in soils or sites that remain flooded for several years. Also, high organic matter soils or Histosols are developed in permanently waterlogged sites or soils because the rate of organic matter destruction is slower than its accumulation. The balance between organic matter inputs and decomposition is the primary determinant of organic matter accumulation or depletion.

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Several hypotheses have been postulated to explain the accumulation of organic matter in submerged soils. They include the deleterious effects on microbial activity of reduction products produced such as hydrogen sulfide or volatile fatty acids and toxic concentrations of ammonia, aluminum, iron, and other cations in soil solution. The absence of electron acceptors such as iron oxides and hydroxides in submerged soils and sediments slows down organic matter oxidation and mineralization. Formation of recalcitrant complex organic molecules with organic matter fractions, e.g., through enrichment of organic matter with phenolics in intensified irrigated rice production system, may render them less available for microbial attack and utilization. Moreover, the net primary productivity of wetlands is higher than other ecosystems. There is need for further research to fully understand the mechanism(s) involved in the accumulation of organic matter in submerged soils as wetlands offer an excellent example of conservation and maintenance of organic matter and storage of organic C.

I. INTRODUCTION

Physical, chemical, and biological processes continually transform organic materials added to soil in the form of plant or animal detritus. Plant litter and the biomass are major contributors to the formation of soil organic matter. Soil organic matter includes decomposition products at various stages of decomposition of organic tissues and products synthesized by soil fauna. Soil organic matter has two major types of compounds: (1) non-humic substances, belonging to identifiable chemical classes such as carbohydrates, and (2) humic substances consisting of a series of brown to dark-brown, high-molecular weight biopolymers (Quideau, 2002). The importance of organic matter in soil cannot be overemphasized in view of its role in the maintenance of soil fertility and crop productivity and for maintaining soil's inherent capacity to perform its crucial functions for ecological and environmental integrity.

The interest in submerged soils or wetlands stems from their importance in agricultural and social productivity and environmental protection. There are various types of wetlands which includes swamps, marshes, shallow lakes and rivers, bogs, mire, salt marshes, mangroves, floodplains, fens, and other ecosystems saturated by water during all or part of the growing season. Wetlands are aquatic to semi-aquatic ecosystems where permanent, prolonged, or periodic inundation creates environment conducive for establishment of aquatic life. Wetlands are referred to as ecotones or transitional communities as they are often located between land and water, although many wetlands are not ecotones as they are not associated with a lake, river, or stream. For nomenclature, definitions and global distribution of wetlands, the reader is referred to Tiner (2002). Acharya (2002) has discussed the economic benefits and value of wetlands. The extent of world's wetland is estimated to be 7–9 million km^2 and occupy about 4–6% of the earth surface (Lefeuvre and Bouchard, 2002).

For the purpose of this chapter two definitions have been adopted. For general purpose, the submerged soils or wetlands "are those areas that are inundated or saturated by surface or ground water at a frequency and duration, sufficient to support and that under normal circumstances do support a prevalence of vegetation typically adapted for life in saturated conditions" (Reddy and Patrick, 1993). For the purpose of agricultural production systems and related aspects, the definition given by Brinkman and Blokhuis (1986) seems more appropriate. According to this definition, submerged soils or wetland soils are those which "have free water at the soil surface for at least during the growing season of arable crops, or for at least 2 months of the growing season of perennial crops, grasslands, forest, or other vegetation,". Wetlands thus support wetland rice crops or wetland rice and dryland crops. The source of water could be rainwater and/or irrigation water.

The wetland rice production systems in Asia support two or three crops per year under irrigated condition. Wetland rice-based system has been intensified rapidly during the last four decades and covers 22 million ha of South Asia and accounts for about 50% global rice supplies (Cassman and Pingali, 1995). These intensified irrigated rice systems or the double-crop rice and wheat systems contribute handsomely to global food supply. Unlike arable crop production systems, the wetland-based systems are relatively robust and sustainable in the maintenance of soil fertility. It has been argued that wetland soils are better endowed in maintaining fertility, especially their organic matter status (Sahrawat, 1994).

Organic matter is the major source of N to wetland rice because 50–75% of the N in the rice crop even in fertilized rice paddies comes from organic matter (Sahrawat, 1983). Moreover, results with 885 diverse soil samples from wetland rice fields in the Philippines showed that N-supplying capacity of the soils, as measured by anaerobic incubation method, was highly significantly ($p < 0.01$) correlated to soil organic matter content (Sahrawat, 1983). Also, accumulated organic matter in wetland soils improves their general fertility status, cation exchange capacity, and nutrient retention capacity, especially of highly weathered, low activity tropical soils (Sahrawat, 1994). Thus, it is not surprising that plant productivity is linked to organic matter content of the soil (Bauer and Black, 1994). Moreover, organic matter has been proposed as a potential sink for storing atmospheric C in soil profile for mitigating global warming and at the same time increasing soil fertility and productivity (Lal and Bruce, 1999; Izaurralde *et al.*, 2001).

The chemistry of submerged soils and sediments differs considerably from that of their aerobic counterparts. This distinction is mainly caused by the lack of oxygen or anaerobiosis under submerged conditions. Anaerobiosis in submerged soils greatly affects the chemistry, microbiology and fertility of soils

(Ponnamperuma, 1972, 1984a; Patrick and Reddy, 1978; Sahrawat, 1998a; Narteh and Sahrawat, 1999; Kimura, 2000; Liesack *et al.*, 2000). A distinct characteristic of soils or sites that has been under submerged or waterlogged (anaerobic) condition for several years, is the accumulation of organic matter. Accumulation of organic matter, especially in tropical rice paddies is significant when compared to soils under arable cropping under similar conditions, and has often been cited as the basis for sustainable maintenance of fertility of wetland rice soils (Sahrawat, 1994).

However, compared to arable crop production systems, little attention has been paid to understand the mechanisms or bases of accumulation and maintenance of organic matter in wetland rice-based production systems. Various authors have proposed hypotheses for the accumulation of organic matter in wetland paddy soils and natural wetlands. However, no effort has been made to critically review and analyze the literature to establish basis or bases for organic matter accumulation in wetland soils. But synthesis of such information could provide leads for improved and sustainable management of fertility in wetlands, especially those supporting wetland rice based production systems. The question to be asked is why wetland soils accumulate organic matter at relatively higher rates and help maintain soil fertility on a long-term basis. The objective of this chapter, therefore, is to critically review recent literature on accumulation of organic matter in wetland rice soils and develop a conceptual framework for the basis or bases of organic matter accumulation in various wetland soils and sediments. The need for future research is also examined.

II. DECOMPOSITION OF ORGANIC MATERIALS IN SUBMERGED SOILS

A. FACTORS AFFECTING ORGANIC MATTER DECOMPOSITION

Studies on the decomposition of plant materials in anaerobic environment showed that the decomposition rates are slower in the absence of oxygen than in aerobic environment. The reduction in oxygen concentration decreases the decomposition rate of plant residues in soil (Wershaw, 1993). Although the decomposition rates are lessened under anaerobic condition, the release of N occurs at a relatively higher C:N ratio than in aerobic environment because the energy requirement for the bacteria, the main decomposers in anaerobic conditions, is lower than those of heterotrophs in aerobic medium (Acharya, 1935a,b,c; Sahrawat, 1980; Ponnamperuma, 1984 a,b).

A comparative evaluation of decomposition of ^{14}C-labeled plant materials in diverse soils from England, Nigeria and four South Australian field sites, showed that the decomposition pattern was very similar in all soils, except that the net decomposition rate doubled approximately for every 8–10°C rise in mean annual air temperature (Jenkinson and Ayanaba, 1977; Ladd *et al.*, 1985; Ayanaba and Jenkinson, 1990). The results suggest that decomposition rates of plant materials in tropical arable or submerged soils are much faster than in temperate soils because of higher air temperatures.

Recent experimental evidence on the relationship between temperature and litter or organic matter decomposition suggests that the simple assumption that temperature affects the rate constant of the processes may not be valid. This was due to the effect of thermal conditions on the kinetics of C mineralization by changing the estimated percentages of initial material that behave as labile or recalcitrant. According to this finding, the utilization of temperature response functions by simulation models may lead to significant overestimations of soil C losses due to temperature increase (Dalias *et al.*, 2003).

Soil moisture affects the rate of decomposition of plant residues and the rate decreases under flooded conditions after peaking at moisture content of 60% of water holding capacity (Pal and Broadbent, 1975). Doran *et al.* (1988) showed that the optimum water content for aerobic microbial activity is 60% of soil pore space filled with water. This applied to diverse soils with various textural classes. The increase in soil water content above 60% of soil pore space filled with water leads to increased anaerobiosis and decline in aerobic microbial activity. That is the reason why the decomposition and mineralization of plant residues in soils are slower and less complete under anaerobic than aerobic conditions (Reddy *et al.*, 1980; Neue and Scharpenseel, 1987; Murthy *et al.*, 1991; Kretzschmar and Ladd, 1993). Lack of oxygen has a major effect on microbial physiology and decomposition of organic materials in soil.

For example, the first-order rate constant for decomposition of the easily decomposable fraction of rice straw was 0.0054 day^{-1} under aerobic condition compared to 0.0024 day^{-1} under anaerobic conditions. The decomposition rates for the slowly decomposable straw fractions were 0.0013 and 0.0003 day^{-1} for aerobic and anaerobic conditions, respectively (Reddy *et al.*, 1980). The decomposition of alfalfa (*Medicago sativa* L.) in soil under aerobic condition, as measured by carbon dioxide evolution, had rate constants of 0.123 and 0.059 day^{-1}, respectively, for rapid and intermediate phases of decomposition. The decomposition rate constants under anaerobic condition, as measured by the sum of water-soluble C, carbon dioxide and methane production, for the rapid and intermediate phases were 0.118 and 0.024 day^{-1}, respectively (Gale and Gilmour, 1988) (Table I).

Transformation of several pyridine derivatives was most efficient under aerobic condition with oxygen as an electron acceptor. Under anaerobic conditions, most of the pyridine derivatives persisted and were often transformed only after a prolonged or no lag period (Kaiser and Bollag, 1992). Polysaccharides and protein polymers undergo depolymerization reactions and

Table I
First-Order Rate Constants for Anaerobic and Aerobic Decomposition of Alfalfa in a Silt Loam Typic Fragiudult

	Rate constants (per day)	
Decomposition phase	Anaerobic	Aerobic
Rapid	0.118 (0.016)[a]	0.123 (0.011)
Intermediate	0.024 (0.005)	0.059 (0.005)

Adapted from Gale and Gilmour (1988).
[a]Standard error.

structural components such as polyphenols are degraded mainly by oxidation reactions (Wershaw, 1993). While carbohydrates and amino acids from fresh plant materials and litter decompose equally fast under aerobic and anaerobic conditions, structural component mineralization under anaerobic or reduced oxygen levels is hampered by inefficient and slow bacterial hydrolysis (Kristensen *et al.*, 1995).

Similarly, the rates of soil organic matter decomposition and N mineralization are lessened in ill-drained lowland rice fields, apparently due to excessively reduced conditions (Takai and Wada, 1977; Kanke and Kanazawa, 1986; Watanabe, 1984). Providing drainage to ill-drained fields results in enhanced rates of organic matter decomposition and release of mineral N (Kanke and Kanazawa, 1986). A collaborative study on the decomposition of rice straw in submerged wetland rice fields at seven sites in South Korea, Philippines, China, and Thailand showed that there were no great differences in the decomposition rates. The decomposition rates during the cropping season at seven sites in four countries varied from 1.2 to 1.9% day^{-1} (Watanabe, 1984).

Chimmer and Cooper (2003) studied the effect of water table levels on organic matter decomposition and carbon dioxide emissions in a Colorado subalpine fen for two summers in microcosms installed in the fen. It was found that carbon dioxide emissions were lowest at the highest water (6–10 cm standing water above the soil surface) which corresponded to submergence of soil under water. The emissions of carbon dioxide increased with the lowering of water table and were highest when the water table was 0–5 cm below the soil surface.

From this discussion it can be concluded that the rates of decomposition of added organic materials as well as of soil organic matter are slower under anaerobic conditions than under aerobic conditions. As soil water level increases, all soil pores are filled with water and the diffusion of air is extremely slow. The diffusion coefficient of oxygen in water is 10,000 times slower than in air and even a modest oxygen demand for microbial activity cannot be met if large pores are filled with water (Jenkinson, 1988).

Obviously, the lack of oxygen in submerged soils is the most important and dominant factor controlling the rate and pattern of organic material decomposition in anaerobic environments.

III. ORGANIC MATTER ACCUMULATION IN WETLAND SOILS

The accumulation of organic matter in soils is controlled by environmental and pedogenic processes. According to Jenny (1941), organic matter content of a soil is the function of climate, parent material, time, organisms, and topography. The rate of organic matter accumulation also greatly varies among soils (Vijre *et al.*, 2003).

A. FACTORS INFLUENCING ORGANIC MATTER ACCUMULATION

The accumulation of organic matter in arable soils differs considerably from that in submerged or flooded (anaerobic) soils. This difference is caused mainly by lack of oxygen or anaerobiosis. Wetland rice soils have a relatively greater tendency to accumulate organic matter. For example, formation of high organic matter soils including organic soils or Histosols occurs under permanently waterlogged conditions. Organic soils are formed when the rate of organic matter production exceeds the rate of its destruction or decomposition. For this, an anaerobic or low oxygen environment is required (Gorham, 1957).

The amount of organic matter formed in wetland soils depends on the amount of organic material added and its humification coefficient (Wen, 1984). Humification coefficient is defined as the fraction of organic C left or retained in the soil after 1 year of decomposition. The humification coefficient of organic materials varies with their chemical composition. As a general rule, higher the lignin content higher the humification coefficient of the organic material. In addition, soil properties and prevailing climatic conditions also affect humification of organic materials (Wen, 1984). The data in Table II show the range in C content and humification coefficients of some crop residues. Rice roots have the highest humification coefficient (50%) and rice straw/stubble the lowest (23%).

Soil fertility research in paddy soils of China showed that the content of organic matter in paddy soil is related to the soil water regime. The drainage conditions of the soil invariably affect the decomposition and accumulation of organic matter. There is greater accumulation of organic matter in waterlogged or poorly drained soils than in the freely drained soils. These results support

Table II
Humification Coefficient and Carbon Contents of Organic Materials in Submerged Soils in China

Plant residue	C content (%)	Humification coefficient[a]
Rice root	46	0.50
Rice stubble	43	0.23
Rice straw	43	0.23
Wheat, barley and millet stubble	52	0.31
Wheat, barley and millet root	37	0.32
Azolla	43	0.43

Adapted from Wen (1984).

[a] The fraction of C in the soil after one year of decomposition.

the conclusion that there is preferential accumulation of organic matter in waterlogged soils compared to well-drained soils (Table III).

Analysis of soil samples from a long-term experiment at the International Rice Research Institute in the Philippines revealed that soils in plots with higher intensity of irrigated wetland rice cropping had significantly higher content of organic C and total N than those with less intensity of wetland rice (Table IV). Soil samples from plots with triple-crop rice had the highest concentration of organic C and total N, followed by double-crop rice, rice-soybean and dryland rice in the descending order of organic C and total N contents. A survey of soils in South China showed that the amount of organic matter is higher in paddy soil under continuous wetland rice cultivation than in the soil under wetland rice–dryland crop system, evidently as the result of different water regimes (Table V).

In a long-term experiment conducted for 7 years, Ponnamperuma (1984b) found that water regime, dry fallow or flood fallow, and application of rice straw influenced the accumulation of N in a clay soil in a double wetland rice system. Highest N is in the soil accumulated under flood fallow with application of rice

Table III
Effect of Water Regime on Organic Matter Contents of Paddy Soils in China

Location	Water regime	Organic matter (%)
Jiangsu	Waterlogged	3.47
	Well-drained	2.20
Jiangxi	Waterlogged	3.23
	Well-drained	3.08
Guangdong	Waterlogged	3.12
	Well-drained	2.12

Adapted from Cheng (1984).

Table IV
Organic C and Total N Content of Four Soils from the Philippines Varying in Intensity of Irrigated Rice Cropping

Cropping system	Organic C (g kg^{-1})	Total N soil (g kg^{-1})	C:N ratio (g kg^{-1})
Dryland rice	13.0b[a]	1.25b	10.4c
Rice–soybean	13.3b	1.19b	11.2b
Double-crop rice	22.5 (0.31)[b]	1.89 (0.03)	11.9
Triple-crop rice	28.8a	2.45a	11.8a

Adapted from Olk *et al.* (1996).
[a] Means within a column followed by the same letter do not differ significantly ($P < 0.05$).
[b] Standard deviation.

straw and lowest in the treatment with dry fallow, without application of rice straw (Table VI).

Aeration of waterlogged soils through sub-surface or surface drainage enhances the rates of soil organic matter decomposition and N mineralization (Sahrawat, 1983). The soil-drying effect, for example, was marked in four permanently waterlogged Philippine Histosols (pH 5.6–6.2; organic matter 2.2–4.2 g kg^{-1} soil). There was virtual absence of organic matter decomposition and mineralization of organic N in these permanently waterlogged soils, but air drying the soils prior to flooding caused a surge in release of ammonium N (Sahrawat, 1981).

Deep marsh vegetation not subject to drying allows organic sediments to accumulate. Further anaerobic conditions in sediments of discharge wetlands with inflow of ground water persist, leading to organic matter accumulation by a decrease in decomposition rates of organic matter. It has been observed that

Table V
Effects of Rice-Based Cropping Systems on Organic Matter Content of Paddy Soils in South China

Location	Cropping system	Organic matter (%)
Hubei	Continuous rice	2.03 – 2.15
	Rice–dryland crop	1.85 – 1.94
Zhejiang	Continuous rice	3.11 – 5.21
	Rice–cotton	2.01 – 2.87
Taihu Lake Region	Rice–rice–wheat	2.74 (0.94)[a]
	Rice–wheat	2.45 (1.04)
Sanghai suburbs	Rice–rice–wheat	2.14 (0.19)
	Rice–wheat	1.58 (0.14)

Adapted from Cheng (1984).
[a] Standard deviation.

Table VI
Nitrogen Accumulation in Maahas Clay as Influenced by Water Regime and Application of Rice Straw in an Experiment Conducted for 7 Years

Treatment	N accumulation (kg ha^{-1} per year)
Two wetland rice crops with dry fallow	117
Two wetland rice crops plus rice straw with dry fallow	208
Two wetland rice crops with flood fallow	217
Two wetland rice crops plus rice straw with flood fallow	317

From Ponnamperuma (1984b).

the oxidation of organic matter results from aeration during frequent draw down and sulfate reduction during anaerobiosis which in turn results in the consumption of organic matter (Komor, 1992). Also, it has been suggested that if wetlands are drained, much of the oxidizable C is oxidized and the remnant is tightly bound to clay and is inert (Richardson and Bigler, 1984).

Analysis of soil samples from a long-term experiment at the International Rice Research Institute farm in Los Banos, Philippines, which began in 1963, showed that intensive rice ecosystems (two or three crops of rice) could maintain organic matter. Infact, the concentrations of organic matter increased by 5–10% in the past 15 years, despite removal of all above-ground crop residues from the plots during the study. The capacity of the soil to supply indigenous N to rice was sustained as the yield of rice in plots not receiving N fertilizer has remained constant for the past 25 years (Buresh, 2002). These results are in agreement and supplement earlier results obtained at several sites in tropical Asia, that soil organic C levels are maintained or even increased in double and triple cropped long-term rice experiments under irrigated conditions (Cassman *et al.*, 1996). The high losses of soil organic C in the rice–wheat (upland) system contrast with results from continuous double and triple crops of wetland rice due to differences in organic matter decomposition pattern and products under more continuous maintenance of anaerobic conditions (Duxbury *et al.*, 2000).

Craft and Chiang (2002) measured organic matter accumulation and the forms and amounts of soil N and P across transects from fresh water depressional wetlands into longleaf pine-wiregrass forests of southwestern Georgia to evaluate changes in labile vs. recalcitrant N and P. Plant available (nitrate), organic and total N decreased and C:N increased from wetland to upland soils. Nearly all N (97–98%) and most P (50–82%) existed in recalcitrant forms, regardless of landscape position. Wetland soils concentrated total N at higher levels than

Table VII
Water Level, Organic C, Total N and Total P in Surface Soil (0–5 cm) Along a Depressional Wetland-Ecotone-Upland Continuum at Ichauway, Georgia, USA

	Wetland	Ecotone	Upland
Water level, cm[a]	20–40	Saturated	< −30
Organic C,%	3.1 (0.3)[b]	3.4 (0.5)	3.4 (0.3)
Total N, %	0.23 (0.02)	0.13 (0.02)	0.10 (0.01)
Total P, mg kg^{-1}	79 (13)	51(11)	48 (3)

Adapted from Craft and Chiang (2002).
[a] Water levels are measured relative to the soil surface.
[b] Standard error.

upland soil even though organic C and organic matter was uniform across the gradient (Table VII). The results indicated that periodic waterlogging favors sequestration of organic forms of N and P in soil. Wetness also favors N retention more than P resulting in preferential accumulation of organic N over P.

From this brief discussion it can be concluded that under similar conditions, wetland rice soils have a greater tendency to accumulate organic matter compared to soils cropped to rice-arable or dryland crop systems. The organic matter level in soil under intensified wetland rice production system can be maintained without any external input of nutrients. Cropping the soil with dryland crop following wetland rice results in the depletion of organic matter accumulated during the wetland rice crop phase. This effect is equal to the air drying effect on organic matter decomposition and the release of mineral N (Sahrawat, 1983).

IV. MECHANISMS FOR ORGANIC MATTER ACCUMULATION IN WETLANDS

A. Lack of Oxygen or Anaerobiosis

Since oxygen is absent in wetland soils and sediments, this has profound effect on the biogeochemical processes which take place under anaerobic conditions or anaerobiosis (processes that occur in the absence or very low supply of oxygen) in soils. Most soil microorganisms are aerobes including common bacteria and fungi (Coyne, 1999). Thus, under lack of oxygen or anaerobic conditions of wetland soils and sediments, microbial activity is greatly affected. Lack of oxygen is responsible for lessened rate of organic matter decomposition in submerged soils (Howeler and Bouldin, 1971). For example, Tate (1979) while studying organic matter decomposition in peat soils, found that the catabolism rate of several C substrates markedly decreased under anaerobic condition compared to rates in the same soil for an aerobic environment. The catabolism rate for amino acids, glucose and acetate, however, was less sensitive to submergence than aromatic compounds such as salicylate.

There is a shift in the activity of microbial population and the activity of anaerobic and fermentative microorganisms increase at the expense of aerobes. The consequence of this shift in microbial activity is that the biodegradation of organic matter is lessened compared to that under aerobic conditions. Moreover, the decomposition of organic matter via anaerobic respiration and fermentation processes is metabolically less efficient and results in slower decomposition of organic substrates. This leads to a greater net accumulation of organic materials in wetland soils and sediments (Duchaufour, 1998). Cycling and turnover of organic matter is directly related to oxygen availability in soils. Since biodegradation of organic materials is retarded, organic matter and N accumulate relatively rapidly under anaerobic conditions compared to those in well-drained upland soils (Axt and Walbridge, 1999; Craft, 2001).

The accumulation of organic matter in submerged soils leads to formation of a dark surface horizon in mineral soils. It was found that soil profile darkening index had strong correlation with the duration of saturated or anaerobic condition. The thickness and color of surface horizons are strong indicators of landscape hydrology (Reuter and Bell, 2003). Under prolonged waterlogged or anaerobic conditions, organic materials may accumulate to the extent that organic soils or Histosols are developed (Soil Survey Staff, Soil Taxonomy, 1999; Collins and Kuehl, 2001).

To sum up, the absence or low concentration of free oxygen is the most important single factor controlling the rate, pattern and ultimate fate of organic matter in submerged soils and sediments.

B. DEFICIENCY OF NUTRIENTS

It has been observed that decomposition of organic materials is faster in fertile than in infertile soils (Neue *et al.*, 1997). Carbon cycling in soils is closely coupled to those of other nutrients and their availability plays an important role in C decomposition, accumulation and storage. Vijre *et al.* (2003) found that C storage in Danish forest soils is facilitated because of impeded decomposition of the litter in nutrient- poor soils and is not driven by high productivity in nutrient-rich soils.

Nitrogen deficiency (Regan and Jeris, 1970), phosphorus deficiency (Sundareshwar *et al.*, 2003), sulfur deficiency (Golhaber and Kaplan, 1975) have been proposed as the factors for lessened rates of destruction of organic materials in wetland soils and sediments. Deficiency of nutrients such as N, P, and S affect the growth of bacteria, which in turn affect C fixation, storage, and release in wetland ecosystems. Recent study of coastal wetlands showed that P limitation of microbial growth impacted the transformation and availability of N, resulting in influencing C fixation, storage, and release mediated by plants for ecosystem management (Sundareshwar *et al.*, 2003).

Meli *et al.* (2003) studied the microbial respiratory responses to the addition of simple and complex model substrates in soil. They found that the availability of nitrogenous substrate facilitated the utilization of starch by soil microorganisms and reduced the time taken for the maximum respiratory response to occur.

Martin and Fitzwater (1988) found that iron deficiency is limiting the growth of phytoplankton, single-celled photosynthetic organisms that convert carbon dioxide to organic C in the surface oceans, in high-nutrient, low-chlorophyll oceanic regions. As a result of scarcity of biologically available iron, phytoplanktons cannot use excess N and P available in the northeast Pacific subarctic. Since this finding, there has been interest in ocean iron fertilization for increasing dioxide fixation by phytoplanktons. It is postulated that enhanced supply of iron would stimulate photosynthesis, which in turn would lead to draw down in atmospheric dioxide levels during glacial maxima (Martin and Fitzwater, 1988). However, concerns have been raised about the practical feasibility and likely side effects associated with iron fertilization of oceans (Chisholm *et al.*, 2001; Lawrence, 2002; Sahrawat, 2002).

C. LACK OF TERMINAL ELECTRON ACCEPTORS

Principal redox couples in sequence in submerged soils and wetland sediments are: O_2/H_2O, NO_3^-/N_2, Mn (IV,III)/Mn (II), Fe (III)/Fe (II), SO_4^{2-}/H_2S and CO_2/CH_4. The main electron acceptors in submerged soils and wetland sediments include dissolved oxygen (O_2), NO_3^-, Fe (III), SO_4^{2-} and CO_2. The final products of reduction in submerged soils are Fe (II), H_2S and CH_4, although intermediate products such as dissolved H_2 and H_2S are also found in submerged soils and wetland sediments (Gao *et al.*, 2002).

Lack of terminal electron acceptors such as ferric iron and sulfate has been proposed as a factor in slowing down the destruction of organic materials in submerged soils and sediments (Lovley, 1995; Sahrawat and Narteh, 2001; Roden and Wetzel, 2002). Lovley (1995) proposed a model for the oxidation of complex organic matter to carbon dioxide with Fe (III) as the sole electron acceptor (Fig. 1).

Recent research with tropical wetland soils from Africa provided indirect evidence on the involvement of electron acceptors such as iron oxides and hydroxides in the mineralization of organic N (Sahrawat and Narteh, 2001). The results showed that N mineralization under flooded conditions was highly significantly correlated to the amount of reducible iron extracted by ammonium oxalate or EDTA ($p < 0.01$, $n = 15$). Multiple regression of mineralizable N on organic C and EDTA (EDTA–Fe) or ammonium oxalate extractable iron

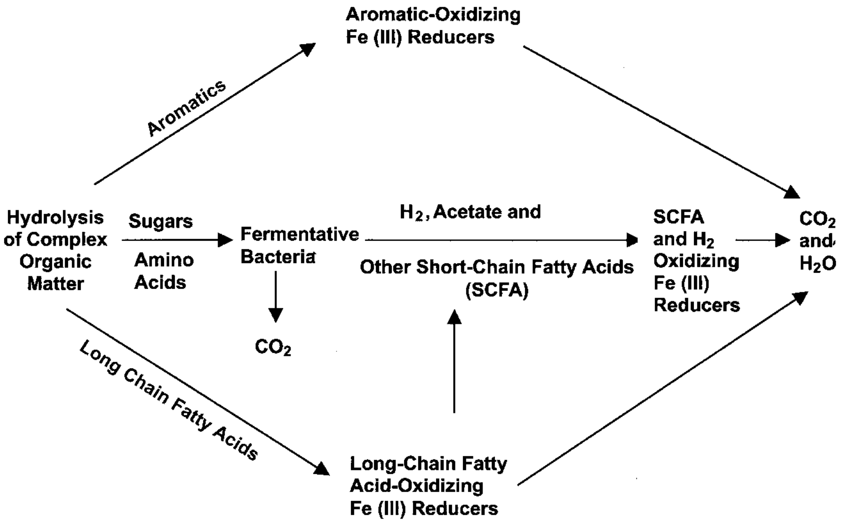

Figure 1 Model for microbial oxidation of organic matter in wetland soils and sediments with Fe (III) serving as the electron acceptor. From Lovley, 1995.

(Amox–Fe) showed that ammonium production in soils under submerged condition can be predicted from organic C and extractable iron by the following regression equations:

$$\text{Mineralizable N or ammonium N produced } (\text{mg kg}^{-1}\text{ soil})$$
$$= 16.4 + 1.320\ \text{Organic C}\ (\text{g kg}^{-1}) + 0.0369\ \text{EDTA} - \text{Fe}\,(\text{mg kg}^{-1});$$
$$R^2 = 0.85 \qquad (1)$$

$$\text{Mineralizable N or ammonium N produced } (\text{mg kg}^{-1})$$
$$= 11.14 + 1.805\ Organic\ C\ (g\,kg^{-1}) + 0.00469\ \text{Amox} - \text{Fe}\,(\text{mg kg}^{-1});$$
$$R^2 = 0.81 \qquad (2)$$

Sahrawat and Narteh (2003) proposed that organic C and reducible iron could be used as N index for assessing the supply of N in submerged rice soils. It was found that soils with higher N supplying capacity, as measured by ammonium released under waterlogged incubation of soils, had relatively higher contents of organic C and reducible iron. On the other hand, soils low in organic C or

Table VIII
Distribution of 15 West African Rice Soils According to Mineralizable N (Min-N) Produced Under Anaerobic Incubation and Associated Organic C and Reducible Iron Extracted by EDTA (EDTA–Fe) or Ammonium Oxalate (Amox–Fe)

Min-N[a] (mg kg^{-1}soil)	No. of soils	Organic C (g kg^{-1})	EDTA–Fe (mg kg^{-1})	Amox–Fe (mg kg^{-1})
86–166	4	23.0–46.0	150–2200	1875–11,412
55–77	5	9.2–23.2	325–800	1100–6750
21–50	6	7.4–15.6	125–600	925–3562

Adapted from Sahrawat and Narteh (2003).

[a] Ammonium produced in soils incubated under waterlogged condition for two weeks at 30°C.

reducible iron released relatively lower amounts of ammonium under anaerobic incubation (Table VIII).

Studies with fresh water wetland sediments demonstrated a direct correlation between first-order Fe (III) reduction rate constants and initial rates of organic C mineralization or decomposition as measured by the amount of carbon dioxide and methane accumulated (Roden and Wetzel, 2002). From the review of recent research on the role of iron as electron acceptor, it was concluded that reducible iron influences organic matter oxidation (Lovley, 1995) and N mineralization or ammonium production (Sahrawat, 2002) in wetland soils and sediments. It was indicated that lack of electron acceptors might lead to slow down in the destruction of carbonaceous materials and increase the accumulation of organic matter in submerged soils and sediments.

The reduction of Fe (III) oxides to Fe (II) is a redox reaction in which Fe (III) oxides serve as the source of reducible iron (electron acceptor) and soil organic matter (CH_2O) serves as electron donor. In this redox reaction, organic matter is oxidized and Fe (III) is reduced to Fe (II) and can be represented by the following equation:

$$Fe_2O_3 + 1/2CH_2O + 4H^+ = 2Fe^{2+} + 5/2H_2O + 1/2CO_2 \tag{3}$$

Precipitation reaction tends to increase Fe (III)/Fe (II) and this drives the reduction reaction ($Fe^{3+} = Fe^{2+} + H^+$) forward. Iron reduction drives the reduction process in submerged tropical rice soils in the humid savanna and forest zones. For example, Narteh and Sahrawat (1999) showed that 4 weeks after flooding of 15 West African rice soils, the soil solution redox potential (*Eh* in mV) can be predicted from the concentration of Fe (II) (mg L^{-1}) in soil solution and solution pH:

$$Eh = 409 - 4.09 \log Fe\ (II) - 59\,pH; \qquad R^2 = 0.99 \tag{4}$$

Moreover, it has been observed that intensive cropping of soils with wetland rice and submergence decrease the amount of free or easily reducible iron in the soil (Mahieu *et al.*, 2002). The implications of these results are that soils under long-term submergence and intensive rice cropping are liable to become deficient in easily reducible iron or electron accepting iron. And this may lead to lessened rates of soil organic matter oxidation and mineralization of soil organic N in submerged soils and fresh water wetlands (Sahrawat and Narteh, 2001; Sahrawat, 2002; Roden and Wetzel, 2002). Reducible iron participates in the redox reactions involved in soil organic matter oxidation and N mineralization in anaerobic soils and sediments.

D. PRODUCTION OF INHIBITORS OF MICROBIAL ACTIVITY

It has been postulated that solubilization of iron (Fe), manganese (Mn), aluminum (Al) and other cations in toxic concentrations in soil solution under reduced conditions or their high concentration in dissolved organic matter might account for slow down in organic matter decomposition in soils and sediments (Hewitt and Nicholas, 1963; Marschner and Kalbitz, 2003). However, Al concentration is unlikely to be in the toxic concentration range in the flooded mineral soils, except perhaps in acid sulfate soils. Because flooding of soils tend to bring the soil pH in the neutral range (Ponnamperuma, 1972; Sahrawat, 1998a). Also, products of anaerobic metabolism in soil such as hydrogen sulfide (H_2S), ammonia (NH_3) or volatile fatty acids have been implicated for deleterious effect on microbial activity and consequent lessened rate of destruction of organic materials in wetland soils (Hallberg, 1973; Ko and Chow, 1977; Takai and Kamura, 1966). The existence of compounds or substances that inhibit microbiological activity is common, especially, in peat soils or Histosols (Gorham, 1957).

Kilham and Alexander (1984) conducted experiments under controlled conditions to establish the factors contributing to the slow turnover of organic materials in flooded soils. The factors investigated included potentially limiting plant nutrients and possible toxicants that might affect microbial activity and organic matter destruction. They concluded that the inhibitory effect of organic acids (acetic, formic, and propionic acids) at low pH values is the reason for the accumulation of organic matter in the soils studied. It is known that undissociated volatile fatty acids at low pH are inhibitory to microbial activity in flooded rice soils (Stevenson, 1967).

E. FORMATION OF RECALCITRANT COMPLEXES

Furthermore, Alexander (1965) suggested that the resistance of some organic substances to microbial degradation is associated with formation of complex molecules with the substrates, which render them less available for microbial utilization and decomposition. Moreover, forming complexes with cations, sesquioxides, and clay minerals in the soil stabilizes the humus fraction of soil organic matter physically and chemically (Oades, 1988; Feller and Beare, 1997; Baldock and Skjemstad, 2000). Wang *et al.* (2003) showed that protective effect of clay on soil organic matter decomposition in a range of Australian soils became significant as the substrate supply and microbial demand approached to an equilibrium state. After this stage soil respiration was dependent on the replenishment of the labile substrate from the bulk soil organic C pool.

Kiem and Koegel-Knabner (2003) provided evidence to show that polysaccharides, mainly those of microbial origin, are stabilized in the long-term within fine separates of arable soils from European long-term agro-ecosystem experiments. On the other hand, lignin (determined by the copper oxide technique) is associated mainly with the coarse fractions of the soil and does not contribute to the refractory C pool.

Olk *et al.* (1996, 2002) provided evidence, which showed that with increased frequency of irrigated rice there was a large increase in phenolic content of organic matter and decreasing abundance of heterocyclic N compounds in Philippine soils. It was suggested that slower lignin decomposition caused by the deficiency of oxygen leads to incorporation of phenolic functional groups in to young soil organic matter fractions. It has been suggested that increased phenolic character of organic matter influence N mineralization, N supplying capacity, and cycling in lowland soils supporting two or three rice crops under irrigated conditions. The results of this research indicated that mobile humic acid and calcium humate fractions of the humic acid were comparatively more sensitive to management of intensified rice paddies than total C or N.

In another study of the nature of organic matter in lowland soil under intensive rice cropping under irrigated conditions in the Philippines, it was revealed that there was consistent enrichment of young soil organic matter with phenols in the two humic acid fractions isolated from lowland soils that have been continuously cropped to rice over the past 11–34 years. However, soil properties, hydrology in the fallow period and the use of mineral fertilizers or green manures had little effect on the accumulation of phenols, although other properties of the humic acid were markedly affected (Olk *et al.*, 1998). It is known that phenolic content and the lignin:N ratio affect the rate of N mineralization from incorporated crop residues and green manures in submerged soils (Watanabe *et al.*, 1991; Becker *et al.*, 1994).

It would thus appear that the presence of phenolics in soil organic matter makes it less labile and retards its decomposition and mineralization in wetland rice soils.

The decomposition of leaf litter from beech (*Fagus sylvatica* L.) and oak (*Quercus robur* L.) trees, as measured by mass losses from litter species and litter types, in three soil types was best predicted by initial concentration of lignin in the litter (Sariyildiz and Anderson, 2003). However, the intra-specific variation in rates of litter decomposition of beech and oak litters from different sites, and differences in their interactions with the two floor materials became too complex for a reliable prediction of the decomposition rates.

The initial decomposition of rice straw in submerged soils of the Philippines was rapid followed by a slow phase. Ultimately, rice straw becomes a part of the soil organic matter with a mean half-life of about 2 years. Moreover, with time rice straw becomes increasingly recalcitrant to further degradation (Neue and Scharpenseel, 1987). The hydrolysis of polysaccharides during anaerobic decomposition of rice straw is limited by the accessibility of the polymers formed rather than by the activity of the hydrolytic enzymes (Glissman and Conrad, 2002). A diversity of physical, chemical, and biological mechanisms selectively protect different fractions of soil organic matter by microbial activity. Most of the recalcitrant C destined for sediment accretion is derived from heavily lignified biomass. Carbon is even better protected in acidic environments, in marine sediments and under low temperature conditions (Bouchard and Cochran, 2002).

In anaerobic environment, organic matter fractions form complexes with ions such as Fe^{2+} (Schnitzer and Skinner, 1966; Jansen *et al.*, 2003) which are stable and resistant to microbial attack. Also, lignins and phenols form stable complexes with amino acids and other N organic compounds (Bondietti *et al.*, 1972; Verma *et al.*, 1975; Martin *et al.*, 1980). Lignins and phenolic subunits of lignins are highly resistant to degradation in anaerobic environment without oxygen (Zeikus, 1980, 1981; Colberg, 1988).

Spaccini *et al.* (2002) studied the effect of humified organic matter, extracted from compost and lignite, on the mineralization of a labile, labeled organic compound (^{13}C-labeled 2-decanol) in soil. It was found that after 3 months of incubation, a higher proportion of C was sequestered in the soil treated with humic acids from lignite compared to humic acids isolated from compost. The higher C sequestration in the lignite humic acid treated soil was due to the hydrophobic nature of the humic acid, which effectively protected mineralization of labile organic compound. It was suggested that the use of hydrophobic substances might increase the biological stability of soil organic matter and also decrease the emission of carbon dioxide from agricultural soils (Spaccini *et al.*, 2002).

Moreover, it has been observed that high contents of carbohydrates, organic acids, and proteins, for which the hydrophilic neutral fraction is a good estimate, enhances the biodegradability of dissolved organic matter in soils. In contrast, aromatic and hydrophobic structures, estimated by UV absorbance, decrease the biodegradability of dissolved organic matter, either due to their recalcitrance or due to effects on enzyme activity (Marschner and Kalbitz, 2003).

Kalbitz *et al.* (2003) also found that the biodegradability of dissolved organic matter in agricultural soils, peats, and organic residues was greatly affected by the organic matter properties such as UV absorbance and synchronous and emission fluorescence. The extent and rate of dissolved organic matter biodegradation from less humified organic materials such as maize straw, litter and fermented layers of forest floors were high resulting in 61–93% being mineralized (measured by carbon dioxide production during 90 days). The dissolved organic matter extracted from agricultural soils was of intermediate biodegradability (17–32% dissolved organic C mineralized). Dissolved organic matter extracted from peats and forest floor layers was relatively stable (4–9% of dissolved organic C mineralized).

It would appear from this discussion that molecular recalcitrance of organic matter fractions stabilizes organic matter, makes it less accessible for decomposition by microbial activity. This results in the preferential accumulation organic matter in submerged soils and wetland sediments.

F. INCOMPLETE DECOMPOSITION AND DECREASED HUMIFICATION OF ORGANIC MATTER

Although organic matter plays a predominant role in the supply of N to wetland rice (Sahrawat, 1983), our understanding of N cycling in relation to organic matter status of wetland soils under intensified rice cropping remains inadequate (Cassman *et al.*, 1996). For example, in tropical wetland soils under intensified rice cropping system, the amount of mineralized N produced or N taken up by rice were not significantly correlated to organic matter status of the soil (Cassman *et al.*, 1996).

A number of studies made on the chemistry of soil organic matter from a diverse group of soils under diverse land use, showed that the incomplete soil organic matter humification was associated with soil submergence. This conclusion was supported by the results of research which showed that the mobile fraction of soil organic matter had less visible light absorption, enhanced presence of lignin residues, lower concentrations of oxygen-containing functional groups, and higher concentrations of hydrogen (Mitsuchi, 1974; Tsutsuki and Kuwatsuka, 1978; Yonebayashi and Hattori, 1988; Ye and Wen, 1991).

Maie *et al.* (2000) studied the humus composition of subsoil of Japanese lowland paddy and upland soils. Differences were observed in the composition of the humus from the paddy and upland soils. Paddy soils had a lower proportion of extractable humus than upland soils, but the amount of sodium pyrophosphate-extractable humic acids was larger in the paddy soils than in the upland soils. The lower content of extractable humic acids in paddy soils was due mainly to the lower amount of sodium hydroxide-extractable fulvic acids. Paddy soils also had lower proportion of extractable humus in total C than upland soils. Paddy and upland soils differed in the composition of humic acids in soil layers below the layer that had accumulated iron. Humification degree of the sodium pyrophosphate-extractable humic acids decreased with depth in the upland soils, but was high even in deeper layers in the paddy soils.

Olk *et al.* (2000) studied the influence of continuous lowland rice cropping on soil organic matter chemistry. It was revealed that the chemical nature of soil

Table IX
Elemental Composition of the Mobile Humic Acid Fraction from Soils of Varying Intensity of Irrigated Rice Cropping Without Application of Fertilizer N

Cropping system	C (g kg^{-1})	H (g kg^{-1})	N (g kg^{-1})	O (g kg^{-1})	S (g kg^{-1})
Dryland rice	518	52.0	46.6	377	6.0
Double-cropped rice	547	59.3	45.8	337	10.8
Triple-cropped rice	553	59.8	44.1	330	13.1

Adapted from Olk *et al.* (2000).

organic matter became less humified with the increasing intensity of irrigated rice cropping and soil submergence. With increasing submergence, the humic acid fractions became less polycondensed and less oxidized or humified with higher sulfur and hydrogen and lower oxygen concentrations (Table IX), lower levels of free radicals, and fewer COOH groups (Table X). Free radical concentrations for the two humic acid fractions studied were highly correlated with the indices of humification. The humic acid extracted from submerged soils had greater capacity for complexing Cu (II), Fe (III) and VO (II) than did humic acid from aerated soils.

Mahieu *et al.* (2002) conducted a comprehensive study of wetland rice soils in the Philippines to identify the long-term effects of intensive lowland rice cropping and soil submergence on soil organic matter properties including its humification. For this purpose, soil samples were collected from fields varying in their previous history of soil submergence. The results showed that soils with two or three rice crops contained 17–29 g C kg^{-1}, while soils with one or no rice crop contained only 13–15 g C kg^{-1}. Intensively cropped soils contained less free or active Fe (10–23 g kg^{-1}) than did soils with one or no wetland rice crop (31–32 k kg^{-1}).

Multinuclear magnetic resonance analysis of two humic acid fractions (mobile humic acid and calcium humate) from lowland rice soils clearly demonstrated that regular aeration of soils promoted soil organic matter humification and that the humic acid fractions were less humified with increasing intensity of irrigated

Table X
Acid Functional Group Composition of the Mobile Humic Acid Fraction from Soils of Varying Intensity of Irrigated Rice Cropping Without Application of N Fertilizer

Cropping system	Total acidity (mol kg^{-1})	COOH (mol kg^{-1})	Phenolic OH (mol kg^{-1})
Dryland rice	5.18	3.10	2.08
Double-cropped rice	3.81	2.00	1.81
Triple-cropped rice	4.33	2.36	1.93

Adapted from Olk *et al.* (2000).

rice cropping. The more humified character of the calcium humate fraction relative to the mobile humic acid fraction was confirmed (Mahieu *et al.*, 2002). The mobile humic acid fraction had higher N and H concentration, lower free radical concentration, and visible light absorption than did the calcium humate fraction in all soils (Table XI). The C : N ratio was larger for the calcium humate fraction (mean 14.0) than for the mobile humic acid fraction (mean 10.9).

The humification process in soils is affected by climatic conditions, especially temperature and soil water regime and the humification processes in soils of the tropical climates may differ from those in temperate climates (Haider, 1992). Nevertheless, soil submergence has an over-riding effect on humification of soil organic matter.

G. HIGH PRIMARY PRODUCTIVITY

The net primary productivity of plant communities in an ecosystem is greatly affected by soil, especially its organic matter content, temperature, water, light, and availability of nutrients.

Wetland soils store higher amount of organic matter in their profiles than done by soils in other ecosystems (Table XII). The amount of organic matter in wetland soils usually exceeds the amount contained in the living and dead vegetation. Some of the wetland Histosols may contain 10–30% or more of their dry mass as C (Paustian, 2002).

In the case of lowland soils, the primary productivity is mainly controlled by nutrient supply (Brinson *et al.*, 1981). The primary production in the flood water of tropical rice paddies and fresh water lakes depends on P concentrations and N is seldom a limiting factor. For example, Sahrawat (1998b) found that natural growth of *Azolla* in irrigated rice fields in West Africa was influenced by P concentration in the floodwater, which in turn was affected by the available P status of the soil. When N becomes limited in the flood water, algae populations shift to nitrogen fixing blue-green algae. In wetland rice paddies, biological nitrogen fixation may contribute 30 kg N ha^{-1} each cropping season. It has been suggested that significant nitrogen fixation occurs only when the N:P ratio is less than 16 (Howarth *et al.*, 1988).

Higher primary productivity of tropical wetlands has been cited as an important factor for the accumulation of organic matter in natural and agricultural wetlands. Many natural and cultivated tropical wetlands have a net primary productivity of more than 1000 g C m^{-2} per year, which is greater than that of any other ecosystem (Neue *et al.*, 1997). The net primary production in floodwater, in addition to that of the soil, is considered as organic matter input to soil.

In a study made at the International Rice Research Institute in the Philippines, it was estimated that the organic matter production in flood water constituted 10 to 15% of the rice plant total gross primary production in a fertilized

Table XI

Concentration of N, H, Organic Free Radicals and Visible Light Absorption at 465 nm (E_{465}) for the Mobile Humic Acid (MHA) and Calcium Humate (CaHA) Fractions Extracted from Soils Varying in Intensity of Irrigated Rice Cropping without Application of Fertilizer N in the Philippines

	N conc.		H conc.		Free radicals		E_{465}	
Cropping system	MHA ($g\ kg^{-1}$ HA)	CaHA ($g\ kg^{-1}$ HA)	MHA ($g\ kg^{-1}$ HA)	CaHA ($g\ kg^{-1}$ HA)	MHA (spins $g^{-1} \times 10^{17}$)	CaHA (spins $g^{-1} \times 10^{17}$)	MHA (OD units g HA-C dm^{-3})	CaHA (OD units g HA-C dm^{-3})
Maize	48.6	40.2	–[a]	–	–	–	–	–
Dryland rice	47.7	36.4	52.0	45.1	1.51	5.26	8.0	14.4
Rice–maize	47.0	40.9	–	–	–	–	–	–
Rice–soybean	48.2	33.9	51.2	40.8	2.45	6.71	7.1	16.9
Double cropped rice	47.0	37.7	56.6	49.3	1.36	3.13	3.4	10.8
Triple cropped rice	44.6	36.0	60.4	53.7	0.81	2.13	3.1	9.3

Adapted from Mahieu *et al.* (2002).

[a] Not determined.

Table XII
Global Carbon Stocks in Soil in Major Ecosystems

Ecosystem	Area (10^6 km^2)	Average C density (Mg ha^{-1})	Soil C stock (Pg[a])
Tropical forests	17.6	123	216
Temperate forests	10.4	96	100
Boreal forests	13.7	344	471
Tropical savannas	22.5	117	264
Temperate grasslands	12.5	236	295
Deserts and semi-deserts	45.5	42	191
Tundra	9.5	13	121
Wetlands	3.5	642	225
Croplands	16.0	80	128

Adapted from Paustian (2002).
[a] Pg is Petagram = 10^{15} g = billion t.

and non-fertilized treatments, respectively (Saito and Watanabe, 1978). Primary productivity and turnover of the aquatic community in a rice field were higher than those of rice roots. A gross primary production of 60–70 g C m^{-2} in 120 days was recorded (Saito and Watanabe, 1978). Yamagishi *et al.* (1980) also reported an average gross organic production of 71 g C m^{-2} in rice paddy fields in Japan, which is similar to the value obtained by Saito and Watanabe (1978). It has been suggested that the photosyntheic biomass production contributes to readily decomposable matter (Saito and Watanabe, 1978). It is estimated that flood water provides a biomass of 1–2 t ha^{-1} per season to fertile wetland rice soils (Neue *et al.*, 1997). Also, flooding increases the readily decomposable soil N in the surface layer (Kobo and Uehara, 1943).

A submerged soil is an ideal medium for both aerobic and anaerobic nitrogen fixation, especially in the presence of rice plants (Ponnamperuma, 1972, 1984a). The surface soil is immediately below the partially oxygenated free water in contact with the atmosphere and immediately above saturated soil devoid of oxygen. The soil below is anaerobic and serves as a source of electron donors to the upper side of the boundary, the electron sink. The boundary itself serves as the interface (Bouldin, 1968). Organic products of anaerobic respiration diffuse upward and provide readily available reduced C energy needed by the nitrogen-fixing organisms living on the aerobic side of the interface, which is an optimum environment for nitrogen fixation by non-symbiotic microorganisms (Reddy and Patrick, 1979). Nitrogen fixation in the anaerobic zone, supplied with cellulose as the energy source, was found to be directly proportional to the interfacial area in soil containers (Magdoff and Bouldin, 1970).

Soil submergence and the presence of the rice plants enhance biological nitrogen fixation in wetland rice (Charyulu and Rao, 1979;

Yoshida and Ancajas, 1971). The maintenance of soil fertility in wetland rice has been believed to be largely due to the fixation of atmospheric nitrogen by diverse nitrogen fixers in the soil. The soil's capacity to supply nutrients, especially N is maintained (De, 1936; Grant, 1965; Grist, 1965; Takahashi, 1965). Moreover, the organic matter formed is conserved under submerged soil conditions.

V. MODELING ORGANIC MATTER IN WETLAND SOILS

Compared to upland or arable soils, relatively little research effort has been devoted to modeling organic matter in wetland soils, although rice is a major food crop and wetland rice contributes handsomely to global rice supply. Moreover, wetlands are considered of critical importance in global C cycle (Paustian, 2002). Nevertheless, initial results with tropical wetland rice soils indicate that N mineralization or ammonium production under submerged conditions can be predicted from organic C and free or reducible iron contents of the soils (Narteh and Sahrawat, 2000; Sahrawat and Narteh, 2001; 2003) (see Section IV.C).

Significant progress has, however, been made in modeling organic matter in arable soils (Coleman and Jenkinson, 1996; Molina and Smith, 1998; Ruehlmann, 1999; Falloon and Smith, 2000; Smith, 2002). For modeling organic matter in wetland soils, useful leads could perhaps be taken from the advances made in modeling organic matter in upland ecosystem. However, for modeling organic matter in wetland soils, consideration must be given to the simulation of oxygen concentration in soil because water and oxygen have a major effect on microbial physiology and decomposition of organic materials and accumulation of organic matter.

There is an obvious need for research on modeling organic matter in wetland soils. Because apart from their predictive value, soil organic matter models are important research tools which can be used for testing various hypotheses on dynamics of C and N in time and space in soils. Soil organic matter models also have application in improving agronomic efficiency and environmental quality by incorporating them into decision support systems (Smith, 2002).

VI. PERSPECTIVES

Unlike in aerobic soils, the destruction of organic materials is slower in the absence or low concentration of oxygen in wetland soils and sediments. Under permanent or long-term waterlogged conditions the rate of accumulation of organic matter is greater than its decomposition and leads to the formation of high

Table XIII

Various Factors or Mechanisms Proposed for Accumulation of Organic Matter and Its Turnover in Wetland Soils and Sediments

- Factors involved in lessened and incomplete decomposition, and decreased humification and net accumulation of organic matter
  - Deficiency of oxygen
  - Deficiency of nutrients (N, P, S)
  - Lack of terminal electron acceptors (Fe^{3+}, SO_4^{2-})
  - Decreased humification of organic matter
  - High net primary productivity
- Production of inhibitors of microbial activity and formation of complex, recalcitrant compounds
  - Formation of complex and stable complexes recalcitrant to microbial degradation
  - Production of reduction products (H_2S, NH_3, volatile fatty acids) deleterious to microbial activity
  - Toxic cations and anions in soil solution

organic matter soils or Histosols. Several factors are involved in the accumulation of organic matter in wetland soils and sediments (Table XIII).

Under anaerobiosis or absence of oxygen, electron-acceptors such as iron oxides and hydroxides are important in organic matter oxidation and ammonium production in submerged soils and sediments (Lovley, 1995; Sahrawat and Narteh, 2001; Sahrawat, 2002). However, the mechanism(s) involved is not fully understood.

The reduction products such as hydrogen sulfide or volatile fatty acids produced during anaerobic metabolism and toxic concentrations of elements such as iron, aluminium, and other cations in soil solution may have a deleterious effect on microbial activity. Complex organic compounds formed with organic matter fractions may render them less available for microbial utilization and destruction. Various authors have ascribed the lessened rates of organic material decomposition to one or the other discussed mechanisms for the accumulation of organic matter in submerged soils.

Evidently, there is a preferential accumulation of organic matter in submerged soils and sediments, although the mechanisms involved are not fully understood. However, there is enough evidence to show that lack of electron acceptors under prolonged waterlogging conditions brings organic matter oxidation and N mineralization to a virtual halt. Since iron oxides and hydroxides are the predominant source of electron acceptors in wetland soils and sediments, they play a dominant role in organic matter oxidation and N mineralization in wetland soils and sediments (Lovley, 1995; Sahrawat, 2002). The availability of iron as electron acceptor in submerged soils also has been reported to suppress methane formation (Watanabe and Kimura, 1999; Jaeckel and Schnell, 2000; Furukawa and Inubushi, 2002; Conrad, 2002).

Thus the availability of electron acceptors, especially iron in submerged soils can have an important influence on the fate of organic materials added or synthesized and the overall pathways of C cycling in submerged soils and sediments. There is need for further research in this important area.

The absence of oxygen in the intensified submerged rice soils slows down the decomposition of lignin from crop-derived materials, leading to incorporation of phenolic moieties into young soil organic matter fractions. This may slow down the oxidation and mineralization of organic matter and N cycling in the intensified irrigated rice-based systems (Olk *et al.*, 1996, 2002). Additionally, the formation of volatile fatty acids produced during anaerobic metabolism of submerged soils has inhibitory effect on microbial activity. The fatty acids have been implicated in the lessening of soil organic matter destruction and hence in its preferential accumulation in flooded mineral and organic soils (Gorham, 1957; Stevenson, 1967; Kilham and Alexander, 1984).

Higher net primary productivity has been ascribed as the important factor for increased soil organic matter in tropical wetland soils (Neue *et al.*, 1997). Flooded soils provide an ideal environment for aerobic and anaerobic microbial activity in its flood water and soil for contributing to higher net primary productivity.

Table XIV
Distribution of Carbon Pools in the Major Reservoirs on Earth

Pools	Quantity of C (Gt[a])
Atmosphere	720
Oceans	38,400
Total inorganic	37,400
Surface layer	670
Deep layer	36,730
Total organic	1000
Lithosphere	
Sedimentary carbonates	> 60,000,000
Kerogens	15,000,000
Terrestrial biosphere (total)	2000
Living biomass	600–1000
Dead biomass	1200
Aquatic biosphere	1–2
Fossil fuels	4130
Coal	3510
Oil	230
Gas	140
Peat	250

Adapted from Falkowski *et al.* (2000).
[a] Gt is Giga t, which is 10^9 t.

It would appear that higher primary production, incomplete and retarded decomposition, and decreased humification of organic matter cause increased organic matter accumulation in many wetland soils (Olk *et al.*, 2000; Mahieu *et al.*, 2002).

Obviously, there is need for future research to fully understand and establish the factors responsible for and the mechanisms involved in the accumulation of organic matter. Mechanisms apart, the wetland soils offer an excellent example of conservation and maintenance of organic matter and storage of organic C. Wetlands are important for sequestering C from atmosphere under anaerobic metabolism. Protection of existing wetlands and creation and restoration of new wetlands will contribute to C sequestration for mitigating greenhouse emissions (Vloedbeld and Leemans, 1993; Mitsch *et al.*, 1998; Bouchard and Cochran, 2002). However, it is important to note that the total amount of dissolved inorganic C in the oceans is 50 times that of atmosphere (Table XIV) and on time scales of millenia the oceans determine atmospheric carbon dioxide concentration and not vice versa (Falkowski *et al.*, 2001). The dissolved inorganic C in the ocean is 19 times that of terrestrial biosphere. In comparison, the quantity of C in the aquatic pool is tiny (Table XIV).

Finally, there is an urgent need for research for organic matter modeling in wetland rice soils by taking possible leads from the advances made for modeling soil organic matter in upland or arable soils.

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