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Effect of flooding on Chemistry of Paddy soils: A Review

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Abstract

An understanding of the influence of flooding on electrochemical and chemical properties of paddy soils provides insight needed in their management for rice production.When an aerobic soil is submerged, its redox potential decreases during the first few days and reaches a minimum; then it increases, attains a maximum, and decreases again asymptotically to a value characteristic of the soil, after 8-12 weeks of submergence. In submerged soils the organic matter is decomposed by facultative and obligate anerobes, the decomposition and assimilation process are slow resulting in the accumulation of plant residues. Redox potential oscillation due to paddy management control community structure and function and thus short-term biogeochemical processes. After flooding microbial reduction processes sequentially use NO_3^-, Mn^{4+},Fe^{3+}, SO_4^{2-} as electron acceptors, accompanied by the emission of trace gases N_2O, N_2, H_2S, CH_4 and due to reduction-induced increasing pH-NH_3. This results in N losses and low N fertilizer use efficiency. However, transport of atmospheric O_2 to the roots via the rice plant aerenchyma modifies conditions in the rizosphere leading to nitrification and methane oxidation and precipitation of Mn and Fe oxides. The large accumulation of soil organic matter observed in some, but not all paddy soils is considered to be due to high input of plant residues and charred materials associated with retarded decomposition underanaerobic conditions. A specific feature of paddy soils is the coupling of organic matter turnover with mineral transformations and fluxes which seem to be intensified by alternating redox conditions. Bioavailability of soil organic N isstrongly coupled to soil organic matter cycling and is a crucial parameter determining crop yield.

Keywords: Flooding, paddy soil, chemical properties, redox potential.

Introduction

Paddy soils are soils that are managed in a special way for the wet cultivation of rice. The management practice, include: (a) leveling of the land and construction of levees to impound water; (b) puddling, plowing andharrowing the water-saturated soil); (c) maintenance of**1-5**cm of standing water duringthe 4-5 months the crop is on the land;(d)drainingand drying the fields at harvest; and (e) re-flooding after an interval which variesfrom a few weeks to as long as 8 months. These operations and oxygen secretion by rice roots lead to the development of certain features peculiar to paddy soils (Ponamperuma, 1972, Narteh and Sahrawat, 1999).

During the period of submergence, the soil undergoes reduction and turns dark gray. Iron, manganese, silica, and phosphate become more soluble and diffuse to the surface and move by diffusion and mass flow to the roots and to the subsoil (Ponamperuma, 1972). When reduced iron and manganese reach the oxygenated surface, the surface of rice roots, or oxidizedzone below the plow sole (De Gee, 1950; Koenigs, 1950; Mitsui,1960; Kyumaand Kawaguchi, 1966, Kirk, 2004), they are oxidized and precipitatedalong with silica and phosphate. Sandwiched between the oxidized surface layer and the zone of iron and manganese illuviation is the root zone of rice with reddish-brown streaks along root channels.

When the land is drained at harvest, almost the entire profile above the water table is reoxidized, giving it a highly mottled appearance. Precipitation in the plow layer is not pedologically of any consequencebecause plowing and puddling redistribute the deposits. But the downward movement of iron and manganese means that these two elements are permanently lost from the topsoil. The eluviated iron and manganese, along with some phosphate, are deposited below the plow sole to produce an iron-rich B1r horizon overlying a manganese-rich Bhorizon. Kyuma and Kawaguchi (1966) regarded reduction eluviation and oxidative illuviation as the soil forming processes characteristic of paddy soils and have proposed the new term "Aquorizem" at the Great Soil Group level to define soils which have the sequence of reductive eluviation/oxidative illuviation. A well-developed paddy soil has the horizon sequence Ap,/A,.../Birg/ Bg/G. Kanno (1957) has described these horizon sequences and their variation with duration of waterlogging, and has proposed a classification of paddy soils based on the depth of the permanent water table. Brinkman (1970) has drawn attention to another soil forming process associated with alternate oxidation-reduction which he calls "ferrolysis." During submergence and soil reduction, the cations displaced from exchange sites by Fe^{-} migrate out of the reduced zone and are lost. When the soil is drained and dried, the reduced iron is reoxidized and precipitated, leaving H+ions as the only major cation. The soil is acidified and the clay disintegrates.

Over the past few years, work on paddy soils has mostly been confined to microbiology and concerns about greenhouse gas emissions (Cai et al, 2005, Conrad, 2007; Kimura et al, 2004). When alternative electron acceptors are consumed, equimolar amounts of CO_2 and CH_4 are end products of anaerobic carbon mineralization (Kirk 2004). Geochemical properties, such as the amount and degradability of organic matter or iron minerals, affect microbial activities. Conversely, microbes affect not only the turnover of their primary substances, but also pH, redox potentials, complexation of metals and solid phase chemistry, adsorption and dissolution/precipitation.(Ingrid et al,2010).

Oxidation-Reduction Potential

Oxidation-reduction is a chemical reaction in which electrons are transferred from a donor to an acceptor. The electron donor loses electrons **and**increases its oxidation number or is oxidized; the acceptor gains electrons and decreases its oxidation number or is reduced (Munch et al., 1978). The source of electrons for biological reductions is organic matter. The driving forceof a chemical reaction is the tendency of the free energy of the system to decrease until, at equilibrium, the sum of the free energiesof the products equals that of the remaining reactants. In a reversible oxidation-reduction reaction, this force can be measured in calories or in volts. Redox reactions in soils are mainly controlled by microbial activity (Ponnamperuma, 1972; Munch et al., 1978; Kirk, 2004). Organisms use organic substances such as carbon sources as electron donors during respiration. Molecular oxygen acts as the preferred electron acceptor as long as it is available. Flooding the field for subsequent rice cultivation cuts off the oxygen supply from the atmosphere, the microbial activities switch from aerobic to facultative and to anaerobic fermentation of organic matter where alternative electron acceptors are used.

In the absence of oxygen, facultative and obligate anaerobes use **NO_3^-,** Mn(IV), Fe(III), **SO_4^{2-}** dissimilation products of organic matter, **CO_2, N_2,** and even H+ions as electron acceptors in their respiration reducing **NO_3^{2-}**to **N_2,** Mn(IV) to Mn(II), Fe(III) to Fe(II), **SO_4^{2-}**to **H_2S, CO_2**to **CH_4, N_2**to **NH_4,** and H+ to H_2(Ponnamperuma, 1972). Also, anaerobic respiration produces substances that reduce soil components chemically (Bloomfield, **1951).** Thus the switch from aerobic to anaerobic respiration ushers in the reduction of the soil

The requirements for soil reduction are the absence of oxygen, the presence of decomposable organic matter, and anaerobic bacterial activity. The course, rate, and degree of reduction are influenced **by** the nature and content of organic matter, temperature, the nature and content **of** electron acceptors, and **pH.**Also, air-drying a wet soil intensifies reduction after submergence (Aomine, **1962;** Yoshizawa, **1966)** and **N,** P, K fertilizers accelerate reduction in soils deficient in these nutrients (Chiang and Yang, **1970).**

When an aerobic soil is submerged, its pH decreases during the firstfew davs (Motomura, 1962; Ponnamperuma, 1965), reaches a minimum, and then increases asymptotically to a fairly stable value of 6.7-7.2 a few weeks later. The overall effect of submergence is to increase the pH of acid soils and to depress the pH of sodic and calcareous soils.

Rice that is grown in submerged paddy soils form aerenchyema which enable the transport of atmospheric oxygento the roots (Armstrong, 1971, Begg et al., 1994)., where a higher redox potential (Flessa and Fischer, 1992; Tyagi et al., 2004) mediates the detoxification of Mn^{4+}, Fe^{2+} by oxidation and results in the precipitation of Mn and Fe oxides in the root apoplast, which is the formation of these plaques which can restrict the acquisition of phytotoxic elements. The critical Eh-value for Fe reduction and consequent dissolution is 100 mV at pH 7. However, different soils vary in the critical redox values for iron transformation (Fiedler et al., 2007).

Microbial Activity

The different anaerobic reduction processes are accompanied by emission of gasses, such as NH_3,N_2O, N_2, H_2S and CH_4. The initial rise in pH at the beginning of reduction processes after flooding and consumption of CO_2 by algae in the water layer promotes gaseous losses of ammonium as NH_3(Kogel-knabnernet al., 2010). Furthermore, N losses via nitrate also play an important role, as nitrate is highly mobile and can leach easily to deeper soil layers or can be used by microbes as an alternative terminal electron acceptor under anoxic conditions, which leads to stepwise reduction to nitrite, NO, N_2O and N_2. Therefore not surprisingly, N fertilizer use efficiency may frequently fall below 35% (DeDatta, 1981, Cao et al., 1984)

Denitrification is brought about by a large number of bacteria and fungi which include heterotrophic and autotrophic species (Painter, 1971). These facultative organisms transform nitrate to nitrogen and its oxide, only at very low oxygen concentrations (Skerman and MacRae, 1957;Bremner and Shaw, 1958; Greenwood, 1962; Turner and Patrick 1968) have shown theoretically that nitrate will become undetectable in water only at an infinitesimal partial pressure of oxygen (Ponamperuma, 1972).

In most rice systems, methanogenesis is the most important terminal process in carbon mineralization. Due to the radiative forcing caused by methane, much work has been done on emissions. Emissions can be quite different depending on water management, mineralogy, rice cultivar, fertilization and local climate (Caoet al., 2001). Flooded rice paddies are one of the major biogenic sources of atmospheric greenhouse gas methane (Liesack et al., 2000). Overall, wetland rice fields contribute about 10-25% to global CH_4 emission (Neue et al., 1997). Crop rotation with flooded rice in summer and upland crops such as wheat, vegetables in winter reduces methane emission compared to repeated cropping with rice (Cai et al., 2005).

Organic matter

The decomposition of organic matter in a submerged soil differs from that in a well-drained soil in two respects: it is slower; and the end products **are** different (Ponnamperuma, 1972). In a well-drained soil, decomposition of plant residues is accomplished **by** a large group of microorganisms assisted by the soil fauna. Owing to the high energy release associated with the aerobic respiration of these organisms, decomposition of substrate and synthesis of cell substance proceed rapidly (Ponnamperuma, 1972). The bulk of freshly added organic matter disappears as **CO_2,** leaving a residue of resistant material, chiefly altered lignin. Also, there is a heavy demand on nutritional elements, especially nitrogen. In submerged soils, the decomposition of organic matter is almost entirely the work of facultative and obligate anaerobes. Since anaerobic bacteria operate at a much lower energy level than aerobic organisms, both decomposition and assimilation are much slower in submerged soils than in aerobic soils. The accumulation of plant residues in marshes and in underwater sediments (Degens, 1965) illustrates this point.

The most striking difference between anaerobic and aerobic decomposition lies in the nature of the end products. In a normal well drained soil the main end products are CO_2, nitrate, sulfate, and resistant residues (humus); in submerged soils, they are **CO_2,** hydrogen, methane, ammonia, amines, mercaptans, hydrogen sulfide, and partially humifiedresidues (Ponnamperuma, 1972).

Paddy soils are characterized by large carbon input via organic fertilizers and plant residues (Tanji et al., 2003). It is commonly accepted that water logging associated with rice cropping enhances accumulation of soil organic carbon (Neue et al., 1997; Lal, 2002). But according to Kirk (2004) wetland rice soils do not have particularly high organic matter contents. Rates of decomposition of added organic materials as well as of soil organic matter are considered to be slower under anaerobic conditions than under aerobic conditions, leading to a relatively greater tendency to organic matter (Sahrawat, 2004).

Nitrogen

Nitrogen occurs in soils and sediments chiefly as complex organic substances, ammonia, molecular nitrogen, nitrite, and nitrate. Transformations that they undergo are largely microbiological interconversions regulated by the physical and chemical environment (Ponnamperuma, 1972). The main interconversions may be depicted asfollows:The mineralization of organic nitrogen in submerged soils stops at the ammonia stage because of the lack of oxygen to carry the process via nitrite to nitrate. **So** ammonia accumulates in anaerobic soils, anoxic waters, and in anaerobic sewage digesters (Ponnamperuma, 1972). Ammonia is derived from anaerobic deamination of amino acids, degradation of purines, andhydrolysis of urea. Less than **I**% comes from nitrate reduction (Woldendorp, 1965).

Nitrogen release from decomposing organic matter is one of the crucial parameters determining biomass production and crop yield (Olk ,et al., 1996).

To improve the N balance, organic amendments like wheatstraw may help to immobilize the liberated N in better developing biomass (Pande, 2005; Pande and Becker, 2003). If combine with N fixation, e.g. by intercropping with green manure legumes, a positive N balance has been detected. Also, organic fertilization with green manures like white clover and hairy vetch helped to improve the N supply, with higher N use efficiency for the incorporated fertilizers than for the surface applied manures ((Asagi and Ueno, 2009). However, to sustain crop growth it must also be assured that the additional N is not sequestered in unavailable N forms by mechanisms outlined above. Olk et al., (2007) showed nitrogen mineralization was inhibited in rice-rice rotation with anaerobic decomposition compared with better aerated treatments. The authors thus suggest increased aeration of rice soils through aerobic decomposition of crop residues or crop rotation as a promising management technique for improving soil N supply in lowland rice cropping.

Conclusion

Paddy **soils** develop in a unique management system that controls redox driven processes affecting mineral transformation and microbial mediated turnover of organic matter. The vertical and horizontal redox gradients formed in a paddy soil have a considerable effect on bacteria, fungi, and archea in those microhabitats.

In contrast to the often observed fact that permanent strong reducing conditions effectively slow down mineral weathering, alternating redox conditions occur in paddy soils and depending on mineral assemblages, have different consequences for mineral weathering. Redox processes trigger the transformation of minerals and are responsible for the mobility of elements.

Since the abundance of electron donors from soil organic matter and dissolved organic matter enhances the changes of structural Fe^{3+} in clay minerals a direct link of biodegradation of organic matter associated with soil minerals and the status of iron in minerals.

Interactions between redox potential, pH, solubility of organic matter and its biodegradation seem to play a decisive role for the biogeochemistry of paddy soils. The availability of organic carbon for microbial degradation is of special interest, because in wetland soils such as flooded rice fields the anaerobic fermentation of soil organic matter leads to release of methane and denitrification losses of nitrogen. To minimize these losses and to optimize paddy management in terms of environmental sustainability, we need quantitative understanding of coupling of organic matter, N, and mineral transformations and fluxes and how they are regulated by redox potential, degree of soil development and microbial community structure and function.

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