Nitrogen fractionation and its mineralization in paddy soils: a review

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Nitrogen (N) is the most yield limiting nutrient for paddy soils, an advanced knowledge about N behaviour, soil organic matter and their measurement and analysis should be known to optimize the yield through efficient mineral N fertilizer use. This paper aims to summarize published information on prediction of N mineralization in the paddy field. This review has been prepared by comprehensive studies of various published articles, books, proceedings and available in the libraries and online. N in the soil is largely organic, and mineralization of soil organic N is a key process for the supply of N to paddy soils because half to two-third of total nitrogen taken up by rice crops even in N fertilized rice paddies comes from the soil N pool. The need to estimate and predict N mineralization has long been recognized in making N fertilizer recommendations, but, till now there is no consistent methodology to estimate N mineralization and still soil scientists have keen interest to find out the reliable, accurate and easily measurable parameters that can predict N mineralization. Particularly for (sub) tropical soils little work has been done within this frame and even less is known on the prediction of N mineralization in paddy soils. Several physical and chemical analysis methods proposed in the literature to measure and predict mineralizable N. Recently soil organic matter fractionation methods are also practiced which are comparatively simple and easy than others. A number of approaches have been used to model and thus describe N mineralization kinetics in soils. This paper reviewed and presented a comparative description of some approaches for predicting N mineralization in the paddy soil.

Key words: Organic N, fractions, mineralization, prediction, paddy soil.

Introduction

Rice is the world's single most important food crop and a primary food source for more than a third of the world's population (Khush, 1997). There are 113 rice producing countries in the world: 30 in Asia, 27 in America, 41 in Africa, 11 in Europe and 4 in Oceania (Nguyen and Tran, 2002). The rice plant is native to tropical and subtropical southern Asia and south-eastern Africa and

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among the rice producing countries most are in tropical zone. Rice is a semi aquatic cereal, typically grown on low-lying land that is flooded for at least part of the growing season. In Asia, where over 90% of the rice in the world is produced, the low land rice soils are typically puddled (De Datta, 1981). Indeed, lowland rice makes a major contribution to global rice supply.

Nitrogen is the most important nutrient in rice production and is required in large quantities and it is most commonly limiting to rice yield (Hasegawa and Horie, 1994). Mineralization of soil organic N is a key process for the supply of N to tropical wetland rice (Manguiat et al., 1996). N mineralization means a process in which N turned into inorganic N (NO_3-N and NH_4-N) from organic N with the help of soil animals and microorganism (Yan and Jing, 2003). Inorganic N is the main type of soil N that can be directly absorbed and utilized by plants, but only accounting to 1% in the total soil N (Das et al. 1997). The N mineralization rate determines the availability of N for the plant growth.

The mineralization process is influenced by a number of factors, such as: soil type, organic matter content, total N availability, C:N ratio, pH, temperature, soil moisture, drying, level of soil acidity, supply of inorganic nutrients and soil/plant interactions (Haynes, 1986). The climate, soil type, organic content, etc. in tropical areas is different from the temperate regions and these different environmental conditions influence N mineralization in different way. N mineralization also influenced by different vegetations (type and their cultural practices), even when they are grown in same type of soils (Vitousek et al. 1982). The behaviour of N mineralization in wetland soil is markedly different from its behaviour in dry land soil. Anaerobic conditions in wet soils result in the accumulation of ammonium, instability of nitrate, and a lowered nitrogen requirement for organic matter decomposition (Savant and Datta, 1982). An understanding of the behaviour of nitrogen in wetland rice soils is a necessary prerequisite for improving growth and yield and improving the productive efficiency of fertilizer N (Masayna et al. 1985). But studies on tropical wetland rice soils are, however, very limited (Manguiat et al. 1996). The objective of this study was to critically review the current literature about the nitrogen mineralization in paddy soil.

Nitrogen in soils

Nitrogen (N) is a major nutrient for all living things on Earth and plays a central role in regulating the composition, structure, and function of ecosystems (Galloway et al. 2004; Fang et al. 2009; Leip et al. 2008). N is crucially important component for all biological life, particularly sensitive to human activities, such as fertilization and cultivation (Zhang et al., 2008; Fang et al.

2008). The soil N cycle is the most important nutrient cycle from the point of view of nutrient management, since N is the most important nutrient for obtaining a good crop production and quality, but also because N has a major impact on the quality of the environment through the various pathways of N losses. Moreover, the N cycle is very intimately linked with the C cycle and the cycles of other nutrients in soil. Nitrogen occurs in several chemical forms these are varying greatly from the proteins of solid organic matter to gaseous ammonia. These forms are classified as either organic or inorganic N. Inorganic forms include ammonium (NH_4^+), ammonia (NH_3), nitrate (NO_3^-), and nitrite (NO_2^-). Inorganic forms of N are the "available" forms that plants and microorganisms can use or that can move in the soil as water moves through it.

Organic forms of N are found in compounds such as amino acids, protein, and more resistant N compounds (ultimately, humus). Organic N comprises over 90 percent of the N found in soil (Pulford, 1991). Most N in the soil is in the unavailable organic form. This is N that has been taken up by plants or other organisms and then incorporated into soil organic matter when the plants die and decompose. In bio-solids, the majority of N added to the soil is in organic forms; the remainder is in inorganic forms (NH_4^+ and NO_3^-).

Nitrogen transformation processes

Nitrogen exists in a number of chemical forms and undergoes chemical and biological reactions. The most important processes of the N transformations are in the soil viz., biological nitrogen fixation, immobilization, aminization, ammonification, nitrification, denitrification, volatilization and leaching (Marzluf, 1997). Soil organic matter is decomposed by microorganisms and nitrogen is transferred into organic nitrogen components. The organisms get carbon and energy from the breakdown of organic nitrogen (protein, amino acids, and nucleic acids), while an excess of nitrogen is released as inorganic ammonium (NH_4). In warm, well-drained soil, ammonium transforms rapidly to nitrate (NO_3-) by the process of nitrification. Nitrate is the principle form of nitrogen used by plants. It leaches easily, since it is a negatively charged ion (anion) and is not attracted to soil clay. The nitrate form of nitrogen is a major concern in pollution as well. When soil does not have sufficient air or oxygen, such as when the soil is waterlogged, denitrification occurs. Microorganisms use the oxygen from NO_3- in place of that in the air and rapidly convert NO_3- to nitrogen oxide (NO_2) and nitrogen gases (N_2). If the waterlogging is temporary, the denitrification process will stop when the soil dries.

Nitrogen fixation is the conversion of nitrogen gas (N_2) to ammonium (NH_4^+) - either by free living bacteria in the soil or water, or by bacteria in

symbiotic association with plants (eg. legume symbiosis). Soil microorganisms use nitrate and ammonium nitrogen when decomposing plant residues. These forms of nitrogen are incorporated temporarily into the microbial cells in the process of immobilization and inorganic N convert into organic N (Alexander, 1977). Another process is nitrogen mineralization by which organic N is converted to plant-available inorganic forms. In the past few years, results from a number of studies have confirmed that some plants are able to directly utilize and generally prefer amino acids over inorganic N (Henry and Jefferies, 2003). This contradicts the traditional views of the terrestrial N cycle that plants are not able to access the organic N directly without depending on microbial mineralization to produce inorganic N. Nitrogen mineralization is highly dependent on environmental conditions (Wang *et al*. 2004). Among the environmental factors, temperature and moisture are most important for influencing nitrogen mineralization. Rate of mineralization goes faster with warm temperature and colder temperatures slower rates (Ross and Bridger, 1978), but less sensitive to soil water content (Wang *et al*. 2004). C:N ratio is another important factor which affects the mineralization.

Soil nitrogen mineralization and immobilization balance

Soil mineralization and immobilization processes determine the plant-available nitrogen pool. The equilibrium between mineralization and immobilization is influenced by such factors as temperature, moisture, oxygen, microbial populations, and the carbon and nitrogen contents of the organic material (Evangelou, 1998). The carbon-to-nitrogen (C:N) ratio is often used as an indication of whether mineralization or immobilization will occur. When surface soil layers have a C:N ratio greater than 30:1, then immobilization is highly likely to occur. When the C:N ratio is below 20:1, N mineralization is likely to occur. When the C:N ratio is between 20-30:1, both mineralization and immobilization may occur but they will generally balance.

Fractionation of soil nitrogen to predict nitrogen mineralization

Measuring and predicting nitrogen mineralization

Estimating an optimum dose of N fertilizers for crops is important from an economic as well as an environmental point of view. Excess amounts of fertilizer leads to low N recoveries in crops, NO_3^- accumulation in the soil profile (Benbi, *et al*., 1991) and increased leaching of NO_3^- into streams or groundwater. Estimates of fertilizer rates depend on crop N requirements and the soil's ability to supply N, which is difficult to quantify (Benbi and Richter,

2002). Mineralization converts the unavailable N form to available N form for plants. Accurate prediction of the net N mineralization dynamics in soil is important for developing appropriate fertilization strategies, which maintain or increase productivity while minimizing adverse N impacts on the environment (Wang *et al.* 2004). There are several methods for measuring and predicting nitrogen mineralization. Most commonly N mineralization can be assessed from the evolution of the mineral N content in the soil either in the field or in the lab. However, such procedures are time consuming and therefore recently research has focused on using physical (3.2.2) or chemical (3.2.3) fractionation methods to search for usable N mineralization predictors.

Field methods

N mineralization can be assessed by measuring mineral N profile in a given field as a function of time and can be derived from a simple N balance as follows (Kanagaratnam, 2009) :- *N min (end) – N min (initial) = net N mineralization*. Where *N min (end)* - implies the final measurement of mineral N on soil profile and *N min (initial)* – implies the initial mineral N measurement on soil profile.

Laboratory methods

Incubation of soils in the laboratory under controlled environmental conditions is a technique that is often used as a measure for mineralizable or potentially available organic N. Mostly aerobic incubation techniques are used, i.e. soil is incubated under free oxygen exchange with the air. Both leaching methods as well as destructive sampling are used. In leaching methods small samples of soil are mixed thoroughly with quantities of pure quartz sand in tubes and then incubated under well specified conditions of temperature and moisture. An obvious drawback to this incubation method is the complete disturbance to the soil during mixing with quartz sand. During the incubation the frequent leaching of the soil creates rather artificial conditions that will undoubtedly influence the mineralization process. Laboratory incubations also can be done with larger number of destructive soil samples. This method can overcome most of the drawbacks of the leaching method. In this method, at predetermined time intervals samples are taken by removing intact soil samples or by taking subsamples that are analyzed subsequently for mineral N. There are some advantages on this method because here more realistic soil conditions with destructive samples can be incubated and there is no need to leach the samples (Kanagaratnam, 2009). Incubation methods have the disadvantage of

being time consuming and this is the another reason why they have not been more widely adopted.

Calculation of N mineralization rates

Nitrogen mineralization can be calculated by fitting simple kinetic models such as first-order kinetic models (Stanford and Smith, 1972) to soil N temporal data. Other than simple models, models like sigmoid, hyperbolic and single exponential and the double exponential models plus linear models have been widely used to describe inorganic N production from soil or amended organic materials (Wang *et al.* 2004). At high temperature during long term incubations, N mineralization is measured by first-order kinetic model to predict and determining net nitrogen mineralization and the first order kinetics are proceed with following assumed way (Broersma *et al.* 1996)

$$N_m = N_o (1 - e^{kt}) \qquad (1)$$

Where N_m is the cumulative net N mineralized up to time t (week);
k is the invariant rate constant (week^{-1});
N_0 is defined as the potentially mineralizable N pool at time 0.

The first derivative of equation (1) is

$$dN_m/dt = (N_o.k)e^{-kt} \qquad (2)$$

The first derivative shows that the rate of mineralization decreases with time and that it is a function of N_0 *and k. At t = 0,*
$(N_o.k) e^{-kt} = (N_o.k) e^0 = N_o.K$

For incubations at lower temperatures, or for shorter duration, then zero order kinetics are often assumed.
N (t) = Kt   With k: zero order N mineralization rate

Satisfactory predictions of net N production in the field have been achieved by Stanford *et al.* (1977) using the kinetic models determined from laboratory incubation.

Physical fractionation methods

Fractionation has been used widely to determine the molecular size, mobility, and availability of dissolved organic matter (Kiikkila *et al.* 2006).

However, there have been few studies carried out to fractionate soil organic N in soil. Soil organic N can be fractionated physically based on their size and/or density. Christensen (1985) used ultrasonic dispersion method for fractionation and found 47-78% of the soil N in the clay fraction, 20-33% of the soil N in silt fraction and 9-11% in sand fraction. By using this same method, Christensen and Sorensent (2006) described the distribution of whole soil labelled organic N as: clay 77-91%, silt 4-11% and sand <0.5%. Whitney and Zabowski (2004) also found soils with a coarse fraction (>2-mm) having 0.3-37% of average total soil N and Amelung *et al.* (1998) found clay fraction (<2 μm) contained about 56% of the total N. Shepherd *et al.* (1996) mentioned that clay textured soils have higher amount of organic N than other coarse textured soils (Table 1).

Table 1. The average topsoil organic N contents of arable sites in the long-term soil mineral nitrogen monitoring scheme (Source: Shepherd *et al.* 1996)

Topsoil Texture	Organic N (t ha^{-1} to 25 cm depth)	
	Mean	Range
Clay	11.7	8.0-13.6
Clay loam	7.5	5.0-12.0
Sandy clay loam	6.4	4.3-9.0
Silty clay loam	6.3	4.0-12.6
Sandy loam	4.7	2.7-7.6
Loamy sand	4.3	3.7-4.9

Comparing the N contribution of particle-size fractions to the total N amount, Gerzabek *et al.*, (2001) revealed the following ranking: silt > clay > fine clay > fine sand > coarse sand and they mentioned that generally, the C:N ratios decreased from coarse to fine fractions. Physically uncomplexed and complexed organic matter can be isolated as the light and heavy fraction by density fractionation. The uncomplexed soil organic matter fraction consists of relatively undecomposed plant material, has a wide C:N ratio (Kanagaratnam, 2009). Because of the large C:N ratio, labile organic matter often releases little or no net N but rather slightly occurs N immobilization. Leinweber and Schulten (2000) therefore concluded that organic matter bound to the heavy soil fraction constitutes the primary source of potentially available N in various soils.

Chemical fractionation methods

Hydrolysis and several types of extraction procedures have commonly been used for fractionation of soil organic matter. Potential mineralization has been estimated from chemical extraction methods. Most of the proposed

chemical methods have involved extraction by acid or alkaline reagents. Milder extraction procedures include boiling in water and measuring total N extracted. Autoclaving in 0.01 M $CaCl_2$ (Dolmat *et al.* 1980) and determining the NH_4^+-N released was found to correlate well with N mineralization except for calcareous soil. Other methods involved boiling in alkaline permanganate or in acid permanganate extraction (Stanford and Smith, 1978).These methods correlated rather well with potentially mineralizable N.

Several of the more recent chemical methods have used hot dilute KCI solution as a hydrolyzing agent to estimate the likely release of nitrogen from soils by measuring the amount of organic N hydrolyzed to $NH4^+$-N during 4 hour incubation at 100° C (Burton *et al.* 2007). For example, Table 2 shows different N mineralization indices derived from chemical, physical and biological fractionation methods from a field experiment. Bremner (1949) found 69-87% of the total-nitrogen of the soils was brought into solution by acid hydrolysis (3 ml of 6N HCl/g soil) and concluded that most of the insoluble-nitrogen found after acid hydrolysis is not derived from protein material, and it is suggested that some of this nitrogen is in the form of heterocyclic nitrogen compounds. On the other hand, Purwanto *et al.,* (2007) showed that total hydrolyzable N accounted for 60-99.97% of the soil total N. Among the hydrolyzable fraction, amino-N was the dominant substance in soils, followed by hexosamine N, unknown N, amide N and inorganic N in decreasing order. Cheng and Kurtz (1963) reported that 70-83% of total soil nitrogen was hydrolysed in their study. Sowden *et al.* (1977) showed special interest on nonhydrolyzable N (NH-N) and unidentified hydrolyzable N (UH-N) fractions which constitute between 28% and 34% of the total soil N. Very little is known about the chemical composition of these fractions except that the N in these materials is not protein N, peptide N, amino acid N, nor amino sugar N or NH_3-N (Schulten and Schnitzer, 1998). Estimates of non-protein N ranged from 55% for the tropical soils to 64% for the arctic soils, averaging 61% for all soils. Thus, about 60% of the total N in soils is non-protein N or, conversely, 40% of the total soil N is protein N (Schulten and Schnitzer, 1998). The NH-N fraction is not inert and can be converted microbiologically and chemically to NH_3 and other N-gases. However, the contribution of NH-N to the N-nutrition of plants is not known (Schulten and Schnitzer, 1998). The chemical identity of organic N containing compounds in soils is only partially known, because 20-30% of soil N cannot be hydrolyzed and identified by wet chemical methods. Leinweber and Schulten (2000) extracted and hydrolyzed these non hydrolyzed forms of soil organic N with dithionite/citrate/bicarbonate (DCB) extraction (Figure 1). They concluded that binding of N to pedogenetic oxides renders them non-hydrolyzable (and hence 'unknown').

Table 1. N mineralization indices values (Source: Sharifi *et al*. 2007)

Index	Mean	SD	Minimum	Maximum	CV %
N_{min} 24 wk, mg N kg^{-1}soil	96	21	59	151	21.1
N_0, mg N kg^{-1}soil	101	33	54	197	38.3
k, wk^{-1}	0.08	0.02	0.042	0.14	38.3
N_e, mg N kg^{-1}soil	21.0	9.0	4.3	41.0	42.5
$CaCl_2$–N, mg N kg^{-1}soil	15.9	7.0	4.1	40.1	37.5
KCl-NO_3, mg N kg^{-1}soil	8.6	5.6	1.3	24.9	44.2
KCl-NH_4, mg N kg^{-1}soil	6.2	3.2	1.7	19.5	39.2
$HKCl$-NH_4, mg N kg^{-1}soil	13.4	4.7	5.7	21.6	25.4
$HKCl_{HYDR}$, mg N kg^{-1}soil	7.4	3.6	2.3	16.1	34.2
$NaHCO_3$–205, UV absorbance	1.30	0.35	0.80	2.22	15.3
$NaHCO_3$–260, UV absorbance	0.41	0.14	0.24	0.81	14.2
ISNT, mg N kg^{-1}soil	151	74	62	369	20.6
NaOH-DD N, mg N kg^{-1}soil	319	123	175	605	11.9
PBN, mg N kg^{-1}soil	99	22	65	144	22.1
PBN_{HYDR}, mg N kg^{-1}soil	93	21	60	139	21.7
MBC, mg C kg^{-1}soil	260	167	25	861	38.7
POMC, g C kg^{-1}soil	6.3	3.6	2.5	18.9	19.1
POMN, g N kg^{-1}soil	0.37	0.33	0.02	1.44	52.7

N_e = gross N mineralization in first 2 week, N_0 = potentially mineralizable N; N_{min} 24 week = gross N mineralization in 24 wk;k = mineralization rate coefficient;$CaCl_2$–N = extractable N with 0.01 M $CaCl_2$;KCl-NO_3 = extractable NO_3–N with 1.7 M KCl;KCl-NH_4 = extractable NH_4–N with 1.7 M KCl;$HKCl$-NH_4 = extractable NH_4–N with 2 M 100°C KCl;$HKCl_{HYDR}$ = ($HKCl$-NH_4) minus (KCl-NH_4);$NaHCO_3$–205 = ultraviolet absorbance of 0.01 M $NaHCO_3$ extract at 205 nm;$NaHCO_3$–260 = ultraviolet absorbance of 0.01 M $NaHCO_3$ extract at 260 nm;ISNT = Illinois soil N test for amino sugar N;NaOH-DD = direct distillation with NaOH (50%);PBN = direct distillation with phosphate-borate buffer (pH = 11.2);PBN_{HYDR} = PBN minus (KCl-NH_4);MBC = microbial biomass C by fumigation extraction, POMC = particulate organic matter C; POMN = particulate organic matter N.
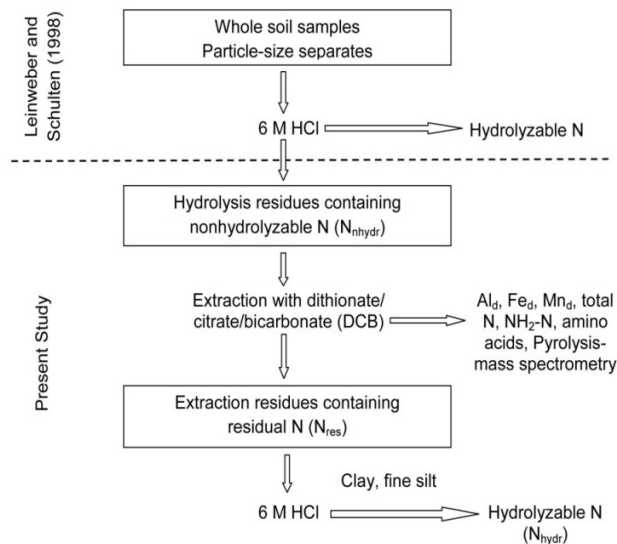
Figure 1. Scheme of N fractionation, DCB extraction and repeated hydrolysis of N-containing compounds

Relatively high proportions of nonhydrolyzable N, to a maximum of 47% of total N was observed by Sharpley and Smith (1995). In some studies, the proportion of nonhydrolyzable N was found to be relatively higher in unfertilized or intensively managed soils; whereas the application of farmyard manure led to an increased hydrolyzability of the organic N compounds present (Leinweber and Schulten, 1997). In contrast, Sharpley and Smith (1995) reported higher proportions of nonhydrolyzable N in manured compared to non-manured soils. Hence, the importance of this organic N fraction in agriculture is not completely clear, probably because of a lack of knowledge concerning its chemical identity and properties.

Nitrogen in paddy soils

Any soil that is used for growing aquatic rice can be called a paddy soil. Paddy soil in this definition is related directly to land use, but not to any particular type of soil in a pedological sense. Paddy soils occur basically in lands with an aquic moisture regime, in floodplains, deltaic plains, fans, and terraces. Fluvisols, Gleysols, and Cambisols are the most common pedological members of paddy soils, but some other members, such as Acrisols and Luvisols, occur among paddy soils on older land surfaces (Kyuma, 2005). Eswaran *et al.* (2001) also listed all the soil orders of soil taxonomy except Gelisols as soils used for aquatic rice cultivation, but they also indicated that

Inceptisols and Ultisols are the most frequently used. Irrespective of their pedological nature, all paddy soils are submerged for at least a few months a year, either naturally or artificially. Managing paddy soils under water is entirely different from managing other soils used for upland crops. Paddy soils are also kept drained for the rest of the year, again naturally or artificially. This cyclic change in micro-environmental conditions exhibits properties not encountered in other soils. All changes further induce enhanced nitrogen availability and its fixation, solubilization of soil phosphates, and so forth (Kyuma, 2005).

Nitrogen mineralization in paddy soils

The flooded paddy soil has three distinct zones established by the prevailing oxidation-reduction or redox potential of the system (Keeney and Sahrawat, 1986) and different N transformation processes are dominant in those different zones – floodwater zone, aerobic zone and anaerobic zone (Figure 2). Floodwater zone has about 50-70mm thickness of water, in which the dominant N-transformation processes are urea hydrolysis, nitrification and ammonia volatilization. The aerobic zone is an oxidized top soil layer of thickness of about few mm to 10mm below the soil surface, and a reduced layer (anaerobic zone) in the rest of the root zone in which the dominant processes are mineralization, denitrification, immobilization, leaching and plant uptake. The available N for plant uptake and leaching out of the root zone depends on the transport and transformations of different N species that undergo in this soil-water-plant-atmosphere system. In submerged or wetland soils, because of the absence or lack of molecular O_2 and N mineralization, *i.e.* the conversion of organic N, stops at ammonium-N production (also termed ammonification). Unlike in submerged soils, in upland soils the ammonium formed is readily oxidized to nitrate via nitrite (termed nitrification) (Sahrawat, 2009). Mineralization can occur in either aerobic or anaerobic conditions. But this process is slower under anaerobic conditions due to less efficient and incomplete decomposition (Sahrawat, 2004).

Mineralization in wetland soils is carried out by a different group of heterotrophs, mainly bacteria (Kyuma, 2004). Because of the lack of oxygen, the oxidation of organic matter and the release of ammonium from organic N in submerged paddy soils and sediments depend on the availability of other electron acceptors such as ferric iron and sulphate (Sahrawat and Narteh, 2001).
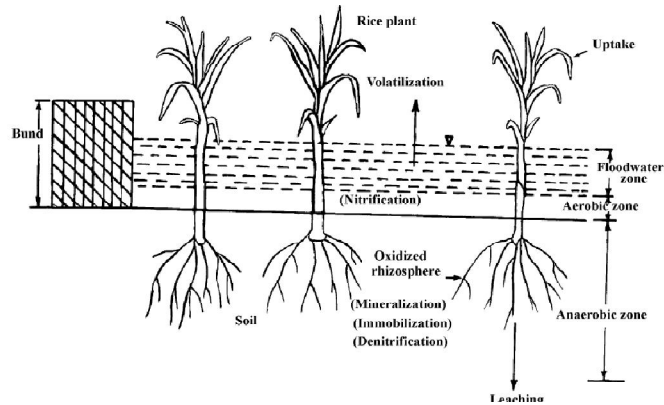
Figure 2. Zoning of an ideal paddy field for N-balance studies (Chowdary *et al.* 2004)

As a result of mineralization of organic N in submerged soils, part of ammonium produced becomes a part of soil solution and the rest remains in the adsorbed phase on the soil exchange complex; and there is a dynamic equilibrium between ammonium in solution and in the adsorbed state (White and Reddy, 2001). In some submerged rice soils, Ponnamperuma (1972) found a considerable portion of ammonia in the solution phase, depending especially on the organic matter content and texture of the soil. In submerged soils, the N in the soil solution is a readily source of N to the growing rice plant (Ponnamperuma, 1972) and forms an important part of the available N pools in wetland rice soils. But sometimes, very large amounts of ammonium-N in soil solution can be toxic to the young growing rice plant in wetland rice soils rich in decomposable organic matter (Ponnamperuma, 1972).

The mineralization of soil organic N in wetland paddy soils is influenced by soil type, environmental and agronomic management factors (Sahrawat, 2009). Among these factors, temperature, moisture regime, microbial activity and microbial biomass, pH, C:N ratio, redox potential, availability of electron acceptors, cation exchange capacity, amount and nature of clay, nature and amount of salts, inputs and nature of organic materials, soil organic matter content and quality and the supply of nutrients such as phosphorus (P) among others, are important for ammonium production in submerged rice soils (Inamura *et al.* 2009). Temperature and moisture regime are perhaps the most important factors controlling the release of ammonium-N in submerged soils (Sahrawat, 2009). In several laboratory incubation studies, it was shown that the mineralization of organic N in soils under waterlogged condition increases with increase in temperature up to even $50°C$ (Ponnamperuma, 1972). Ando *et al.* (1992) reported that the difference in the quantity of N mineralized between 20 and $25°C$ was smaller than that between 25 and $30°C$. In upland paddy soils,

the mineralization results in the formation of nitrate -N as the final inorganic N and nitrification has been reported to be more sensitive than ammonification to high temperature (Sahrawat, 2008).

Table 3. Rate constants for different N- transformation processes

Process	Rate Constant (kg N ha^{-1})	Source
Urea hydrolysis	10^{-6} to 5×10^{-5} s^{-1}	Singh and Kirk (1993)
	10^{-5} s^{-1}	Sahrawat (1980) and Savant et al. (1985)
	0.744 day^{-1}	Jena and Misra (1990)
	0.36-0.56 day^{-1}	Ling and Aly (1998)
Volatilization	1.27×10^{-3} to 1.54×10^{-4} day^{-1}	Chin and Kroontje (1963)
	0.25-0.30 day^{-1}	Jemison et al. (1994)
	0.1-0.8 day^{-1}	Hutson and Wagenet (1991)
	0.043-0.065 day^{-1}	Singh and Prasad (1992)
Nitrification	0.2 day^{-1}	Jansson and Anderson (1988)
	0.2 day^{-1}	Johnsson et al. (1987)
	0.02-2.0 day^{-1}	Rao et al. (1984)
	0.14-1.10 h^{-1}	Mishra and Misra (1991)
	0.04-0.06 h^{-1}	Jena and Misra (1990)
	0.15-0.25 day^{-1}	Ling and Aly (1998)
Mineralization	0.02 day^{-1}	Jemison et al. (1994)
	0.005-0.04 day^{-1}	Hutson and Wagenet (1991)
	0.0126-0.0373 day^{-1}	Seyfried and Rao (1988)
	0.0077 day^{-1}	Stanford and Smith (1972)
	0.019 day^{-1}	Pathak and Sarkar (1995)
	2×10^{-2} day^{-1} (flood water)	Rao et al. (1984)
	2×10^{-2} day^{-1} (oxidized layer)	Rao et al. (1984)
	7.5×10^{-4} day^{-1} (reduced soil layer)	Rao et al. (1984)
Denitrification	0.13-0.18 day^{-1}	Reddy et al. (1978)
	0.1 h^{-1}	Misra and Mishra (1977)
	0.1 day^{-1}	Johnsson et al. (1987)
	0.1 day^{-1}	Jemison et al. (1994)
	0.2 day^{-1}	Jansson and Anderson (1988)
	0.0027-0.0067 day^{-1}	Rolston and Marino (1976)
	0.02 h^{-1}	Jena and Misra (1990)
	0.07-0.08 h^{-1}	Mishra and Misra (1991)
	0.05-0.4 day^{-1}	Hutson and Wagenet (1991)
	0.07 day^{-1}	Ling and Aly (1998)

In summary, Mitsui (1954) described some general unique characteristics of nitrogen transformations in wetland rice soils: (i) N fertility is higher in the flooded rice soils than in the Upland soils; (ii) The surface of the flooded soil and the floodwater accumulate N by recycling or by biological N_2-fixation; (iii)

Surface-applied: ammonium-N is unstable due to nitrification-denitrification. NH_4^+ is stable in reduced soil.

The mineralization in aerobic paddy soil is also influenced by organic matter content and organic matter quality, microbial biomass, the inputs and quality of organic materials (Balkcom *et al.* 2009). While under anaerobic conditions the decomposition of organic N is dependent on the availability of alternate electron acceptors such as ferric iron and sulphate, which are far less efficient electron acceptors than O_2 is (Sahrawat, 2004). In tropics, there are few studies on the mineralization pattern of soil organic N in dried and wet paddy soils. Ando *et al.* (1992) found an appreciable difference in the mineralization potential between the wet soils and slowly mineralizable organic N of the dried soils between changes of soil conditions from wet to dry and the rapidly mineralizable organic N of the dried soil. And they also reported that the reason for this phenomenon remains unknown. Based on a review of published literature, a range for the values of the rate constants of different N transformation processes can be identified from Table 3 (Chowdary *et al.* 2004).

Conclusion

The growth and yield of paddy is largely influenced by the amount of ammonium in soil which in turn is affected by the mineralization of soil organic N. With increasing population, in order to meet the demand of food in the over populated rice growing countries; the farmers are using a lot of nitrogenous fertilizer in an unbalanced way. So, the control over the N flow in a soil- plant system is necessary to produce crops of good quality and minimize environmental pollution. To apply an accurate amount of N fertilizer, we have to first know about N behaviour in the soil and the amount of N supplied to a growing crop from mineralization of soil organic matter. Different N mineralization assessment techniques are available for determining the soil N status on field and laboratory. Each assessment technique has its own limitation, merits and demerits, but to date no single predictor has been identified that can provide reliable estimates of N mineralization. Particularly for (sub) tropical soils little work has been done within this frame and even less is known on the prediction of N mineralization in paddy soils. Controls of mineral soil constituents, soil organic matter quality and inundation period may be important determining factors for N mineralization in paddy soils and these require much more research. Moreover, instead of using inorganic nitrogenous fertilizer, different cultural practices i.e. agronomic management can be used to increase the N mineralization rate, N use efficiency and to minimize NH_3 and

denitrification losses. So, Cultural practices to increase availability of soil N in paddy fields also have to be developed.

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