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Effect of plant residue and water management practices on soil redox chemistry, methane emission, and rice productivity

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EFFECT OF PLANT RESIDUE AND WATER MANAGEMENT PRACTICES ON
SOIL REDOX CHEMISTRY, METHANE EMISSION, AND RICE
PRODUCTIVITY

A Dissertation
Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
Requirements of the degree of
Doctor of Philosophy
in
The Department of Agronomy & Environmental Management

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ABSTRACT

Approximately 5% of rice growing area in Louisiana experience poor seedling or stand development attributed to anaerobic decomposition of excess plant residue, which create strongly reducing or toxic soil conditions. This study investigated plant residue and flooding regime effects on soil properties as related to rice growth and seedling development. Field experiments were conducted at several commercial farms in Southwest Louisiana (which have experienced problem with rice stand development) to relate observed restricted rice growth to soil redox chemistry and other chemical and physical properties. Field experiments were also conducted at the Crowley Rice Research Station in which various rates of rice straw amendment were added to replicate field plots to determine effect on rice growth and methane emission. The study also include greenhouse experiments on plant residue effect on soil chemical properties as related to rice seedling development and growth including effect of plant residues sources (rice straw or alligator weed on rice seedling germination).

These studies showed source and quantity of plant residue significantly affected rice seedling development and germination rates of various commercial rice varieties. Alternating flooded and drained cycles significantly increased growth and grain yield of rice as compared with continuous flooded treatments containing high level of soil plant residue. High rates of plant residue addition increased methane emission (7,350 kg ha\(^{-1}\) season\(^{-1}\)) as compared with treatment receiving no added plant residue (370 kg ha\(^{-1}\) season\(^{-1}\)). Alternating flooded and drained cycles as compared with continuously flooded resulted in a 50% reduction in methane emission and increased grain yield by 30% in treatment receiving 24 t ha\(^{-1}\) plant residue added.
Alligator weed plant residue source had greater effect on rice seedling development as compared with rice straw. Adoption of alternately flooded and drained water management practice, which improves soil chemical properties, can substantially increase rice growth and yield as well as reduces atmosphere methane emission from Louisiana rice soils.
CHAPTER 1

INTRODUCTION

1.1 BACKGROUND INFORMATION

Rice production in the United States is grown under either water or dry seeded cultural system in Arkansas, Texas, Mississippi, Missouri, and Florida (Linscombe et al., 1999; Miller and Street, 1999). In Louisiana, water seeding is the predominant system, but dry seeding also contributes significantly to total production, especially in the northeastern region of the state (Street and Bollich, 2003). Basically, there are three water management practices used in both rice cultural systems: a) delayed flooding, b) pinpoint flooding, and c) continuous flooding (Street and Bollich, 2003). Pinpoint and continuous flooding are the most common practices used in suppressing red rice because the field is maintained in a flooded condition, which limits oxygen for red rice germination (Linscombe et al., 1999). De Datta (1981) stated that sufficient water supply and optimum flooding time of field are important factors for wetland rice production.

Organic matter plays a major role in wetland soil. Plant litter and the biomass are the major source soil organic matter. Soil organic matter can serve as a source of N to wetland rice cultivation (Ponnamperruma, 1984). The aeration of submerged soils through or surface drainage enhances the rates of soil organic matter decomposition and N mineralization (Sahrawat, 1983). However, the adverse effects on crops growing near of the decaying crop residues occur predominantly under anaerobic conditions (Cannell and Lynch, 1984). In high organic matter wetland rice soils, symptoms associated with poor rice root systems often have been observed in the presence of growth-inhibiting substances under extremely reduced conditions (Takijima, 1963). In Louisiana, most of
rice growing area, farmers generally keep several centimeter of water in their rice fields
during the growing season. This condition results in limited \( \text{O}_2 \) supply and enhances
microorganism decay plant matter under anaerobic environments that can cause an
adverse affect on rice growth (Courreges, 2004). Many workers have grouped
physiological diseases such as deficiency of nutrient elements, toxicity of elements,
toxicity of substances (Tanaka and Yoshida, 1970; De Datta, 1981; Dobermann and
Fairhurst, 2000) and hydrogen sulfide (\( \text{H}_2\text{S} \)) toxicity (Gao et al., 2003; Cartwright and
Lee, 2004). In addition, Sass et al. (1991) reported that rice straw incorporation into soil
influences \( \text{CH}_4 \) emission depending on amount of straw added and the method of
incorporation. The incorporation of rice straw also caused and increased \( \text{CH}_4 \) emissions
over the whole season, rice grain yield decrease proportionally (Sass and Fisher, 1995).

The most effective mitigation option for reducing toxicity of decomposed plant
materials to the rice plant and reducing methane emission would be to prevent
submergence of rice fields (Neue, 1993). However, some wetland rice systems usually
grown because fields are flooded naturally during the rainy season. Drainage these rice
fields or preventing from flooded water during the growing season is impossible. Most
of wetland rice in the U.S. grown under flooding condition to control weed such as red
rice, especially in southwest Louisiana. Draining the rice field can cause the decreasing
rice grain yield. For example, Castillo et al. (1992) reported that draining the field for 20-
22 days period resulted in water deficit and rice grain yield was significantly reduced. In
addition, the growth stage of rice must be considered. In this study, we drained the rice
field for 10 days at the fourth week of the growing period (about tillering stage) to
investigate the effect of the decomposition of organic matter under aerobic condition on rice growth, grain yield, and methane emission.

In 2001, we received soil samples from rice farms located near Lake Charles and North Crowley. The samples were identified with problems associated with abnormal growth of rice seedlings and another set of samples were collected from normal growth areas. These samples were analyzed at LSU Wetland Biogeochemistry Institute indicated that the soil samples from the area of poor plant survival contained high levels of organic matter. We also conducted a small pot experiment to observe plant growth. The plants in the high level of organic matter soil showed very poor growth such as small stems, low dry weight, and less survival as compared with the soil with less organic matter, especially in the first two months. However, after this period the plant in pots containing higher levels of organic matter had greater growth than the lower organic matter level. The preliminary experiment indicated that anaerobic decomposition of organic matter was the main factor. We set up both pot and field the experiments to deal with this problem concerning soil redox potential or increasing aeration period in the rice field. We followed rice farming techniques outlines in “water management practices”. We used water management techniques as main plot and organic matter level as subplot.

1.2 RESEARCH OBJECTIVES

This research was designed to determine effects of organic matter (sources and rates) on soil chemical properties, nutrient uptake, growth and grain yield of rice, and methane emission from rice fields. We also investigated the water management practices as remediation options to reduce the adverse effects of organic matter on rice growth and methane emission. The studies consisted of four experiments; two experiments conducted
in the greenhouse and two in the field. The first study was a field experiment observing the effect of plant residue on soil redox potentials, soil chemical properties, and rice growth. The details of this experiment are presented in Chapter 3. The second experiment was conducted in the greenhouse. The rice seeds were grown in pots with different levels of plant residue (rice straw) and two water management practices as main plots. The results of this experiment are discussed in Chapter 4. The third experiment was conducted in the field at the Rice Research Station, Crowley, Louisiana. We imitated the treatments employed in the greenhouse studies but rates of plant residue (rice straw) applied to the soil were higher than used in the greenhouse. The results of this experiment will be described in Chapter 5. The last experiment was conducted in the greenhouse. This experiment was designed to determine the adverse effect of plant residues on rice seedling development and early growth stage of rice. This study emphasized the effect of sources and rates of organic matter on rice seedling development of various rice varieties. The results of this experiment are explained in Chapter 6. In addition, in Chapter 7 we combined the results from all experiments into management techniques that could be used by farmers currently experiencing problems with poor rice stand development.
2.1 Rice Production

Rice (*Oryza sativa* L.) is a major food crop grown under various moisture or flooding regimes. Following wheat, rice is the second largest produced cereal in the world. Rice ecosystems have been classified according to water regimes as upland, lowland, and deepwater (flood-prone) rice ecosystems. Upland ecosystems, rice is grown on dry soil with no standing water. Lowland ecosystems, rice is grown in standing water of less than 50 cm depth. In deepwater ecosystems, rice is grown in standing water of greater than 50 cm depth (De Datta, 1981). Lowland irrigated rice systems accounts about 55% of the global planted area and it contributes three-fourths of global rice production (Dobermann and Fairhurst, 2000). Rainfed rice system is the second in important in both harvested area and rice production. It has been reported that upland and deepwater rice growing area have progressively decreased with the current production accounting for less than 8% of the world rice supply (Dobermann & Fairhurst, 2000).

According to world rice statistics (Riceweb, 2002), global rice harvested area was 147 million hectares in 2002, which a total rough rice production of 576 million tons. These numbers were approximately by 3% less as compared to 2001. China alone contains about 20% of the global rice harvested area represent on about 30% of total rice production. Globally irrigated rice is grown on about 50% of total harvested rice area contributing about 70% of total rice production (IRRI, 2002). Rice is an important source of dietary for human. Guerra et al. (1998) stated that rice provides 35-60% of the dietary calories consume by almost 3 billion people. Demand for rice is projected by the
year 2025 to increase by 60% over the current production in order to meet to growing of world population (IRRI, 2002).

Most of the world’s rice is grown in Asia, which represents 90% of the global rice growing area. In many rice-growing countries, rice systems are intensive cropping systems with a total grain production from double- or triple- crops of 10 – 15 t ha\(^{-1}\) year\(^{-1}\) (Dobermann and Fairhurst, 2000). In irrigated rice culture in the tropics, short-duration rice varieties are usually grown. Although the rice grain yield per area in dry season is greater than wet season, the major rice production in most areas comes from wet-season harvests (De Datta, 1981). With the advantage of irrigation systems, rice production can be increased in areas of the world with optimum climatic conditions such as optimum temperature and high solar energy, particularly in the dry season and also can be adjusted to meet the demand of the world rice market. In rainfed areas, the rice-cropping system is usually one crop per year, where the cropping season (planting and harvesting) is determined by the rainfall patterns. In most of the temperate rice-growing countries in Asia, rice cropping is also determined primarily by the temperature patterns. Globally rainfed rice production represents nearly 45% of total rice cultivation area. The current yield from rainfed rice systems is about 2.0 t ha\(^{-1}\) as compared to 5-6 t ha\(^{-1}\) for irrigated rice (Riceweb, 2002).

Even though new technologies have been adopted in recent year, most rice is still planting by hand. Direct seeding is the preferred planting method in many rice producing countries. This technique requires more seed per hectare but labor requirements are much less for planting a given area as compared to the transplanting method. In some advanced countries, direct seeding is adapted to mechanization such as drill seedling, direct
seedling, and broadcast by airplane. Mechanical method of transplanting operation by machine has not been successful (Efferson, 1994). In contrast, mechanical rice harvesters are popular worldwide.

Rice farming in the United States is considered the most advanced in the world. In order to use water efficiently and produce rice economically, rice fields are leveled with lasers with less than three centimeter difference in elevation. Usually rice seed that has been soaked in water for 24 to 48 hours is used. This pre-germinated seed with high water content will fall into the flooded fields and sink immediately into the mud rather than float and washed in large volume to the edges of the fields (Efferson, 1994).

The leading producers of rice using averages between 1999-2003, are China, India, Indonesia, Vietnam, Thailand, Burma, Brazil and the United States (UNCTAD, 2003). Most rice is consumed domestically or traded in the local market near where it is produced. International market of rice is very small, accounts for 5 % of the total production or about 25 – 27 million tons of milled rice per years. The main rice exporting countries (average from 1998 to 2002) are Thailand, Vietnam, the United States, India, and China, whereas the importers are Indonesia, Brazil, European Union, Bangladesh and Iran (UNCTAD, 2003). Regardless the economics of importing countries, it is projected that the global market will increase by 3 % per year to balance the increase in population of these countries.

2.2 ORGANIC MATTER IN FLOODED SOIL

The decomposition and accumulation of organic matter in flooded soils totally differ from those of upland or aerobic soils. Since oxygen is the most important factor controlling the decomposition of organic matter in rice soils. Howeler and Bouldin,
(1971) noted that lack of oxygen in submerged soil resulted in lower rate of organic matter decomposition. Oxygen plays a significant role as terminal electron acceptors of anaerobic respiration in submerged soil. Usually, soil oxygen is absent within a few hours after flooding. The availability of alternative electron acceptors used by microorganisms in such with no oxygen are NO$_3^-$, MnO, Fe (III), SO$_4^{2-}$ and CO$_2$ depend upon the intensity of reduction. Lovley (1995) reported that lack of electron acceptors such as Fe (III) and SO$_4^{2-}$ resulted in lower rate of organic matter decomposition in submerged soils and sediments. Deficiency of plant nutrients such as N, P, and S have also been reported as the factors for lower rates of decomposition organic materials in wetland soils and sediments (Regan and Jeris, 1970; Sundareshwar et al., 2003; Golhaber and Kaplan, 1995). In addition, drainage of flooded soils which increases oxygen availability enhances the rates of soil organic matter decomposition and N mineralization (Sahrawat, 1983).

Plant materials are the major source of soil organic matter. The term soil organic matter (SOM) usually includes decomposition products at various stages of decomposition of organic materials and products synthesized by soil microorganisms (Sahrawat, 2004). Soil organic matter consisted of two types of compounds: non-humic substances, belonging to identifiable chemical compositions such as carbohydrates, and humic substances consisting of a series of brown to dark-brown, high molecular weight biopolymers (Quideau, 2002).

The importance of SOM for various crop productions has long been documented. SOM management irrigated rice-based cropping systems have been studied widely, particularly for the short-term yield responses to various types of organic matters
amendment such as crop residue, green manures, and animal manures (Olk et al., 2000). However, the long-term effects of SOM properties on crop performance and productivity are not clear. Mahieu et al. (2002) studied the fate of organic matter in wetland rice soils collected from different cropping patterns. The results showed that the soils with low number of crops per year (no or one rice crop) contained less C than the soils with intensive rice cropping system (2-3 rice crops per year). Furthermore, the rice soils with lower crops per season contained more free iron than that of intensive cropping soils.

A number of experiments showed that SOM can serve as a source of N for wetland rice cultivation. For example, Ponnamperuma (1984) conducted a long-term experiment for 7 years in a double cropped wetland rice system. He found that several factors including water regime, dry fallow or flood fallow, rice straw application influenced the accumulation of N in a clay soil. Olk et al. (1996) also reported that the highest N content was observed in the soil under flood fallow receiving application of rice straw and the lowest soil N in the treatment with dry fallow, without any rice straw application. SOM also plays a significant role as a buffer in soil against plant nutrients loss, particularly in the sandy soils or the soils having low cation exchangeable capacity (Olk et al., 2000). The benefit of SOM to crop productivity varies with soil characteristics such as texture, environmental condition, and microbial activities (Olk et al., 2000).

2.3 STRAW MANAGEMENT IN RICE FARMING

Straw is the major organic material source available to most rice farmers, particularly in double- and triple- cropping systems. Rice straw has long been considered an important source of nutrient because it contains about 0.6 % N, 0.1 % each of P and S, 1.5 % K, 5 % Si, and 40 % C (Ponnamperuma, 1984). Straw is also an important source of
micronutrients for rice such as zinc (Zn), which is recommended as a fertilizer addition in some locations, and is the most important factor in maintaining the cumulative silicon (Si) balance in rice (Dobermann and Fairhurst, 2002). Rice straw can also enhance N fixation, particularly rice straw plus mineral N increased number of N-fixing bacteria (Ponnamperuma, 1984).

Straw management methods in rice field vary among locations and countries. Traditional rice cultural practices and economic constraints are the dominant factors influencing straw management. In Asia, where over 90% of rice is produced, the major methods of rice straw management are incorporation, compost, burning, feed or animal bedding, mushroom culture, mulching for orchard or vegetable, fuel for household, straw products or roofing, and manufacture of paper (Tanaka, 1973). Straw managements by most farmers are generally a combination of those methods. Straw management can be classified into two major categories; incorporation (return the straw back to the rice fields), and removal. Each of the straw management method has a different effect on overall nutrient balance and long-term soil fertility (Dobermann and Fairhurst, 2002).

Incorporation of rice straw and remaining stubble into the soil returns most of the nutrients and helps to maintain rice grain yield over the long-term period. Straw incorporation has been reported to improve soil condition and plant growth. For example, Yoneyama and Yoshida (1977) concluded that straw incorporation enhanced immobilization and mineralization of nitrogen. Ponnamperuma (1984) reported that if straw incorporation continued for a sufficient number of seasons in lowland rice culture generally resulted in greater grain yield compared to straw removal or burning. The benefit of straw incorporation is greater in warmer climates where any toxic compounds
released quickly before planting the new crops and causing any adverse effects (Cho and Ponnamperuma, 1971). Straw incorporation in cooler climates might reduce grain yields in initial year but provide benefit in later years after the rate of N mineralization from straw increases (Verma and Bhagat, 1992). The effect of straw on yield of wetland rice depends on management methods, amount of straw, soil fertilizers, and time and duration of application (Ponnamperuma, 1984). The disadvantages of incorporation have also been documented. For example, the improper timing of straw incorporation can inhibit growth of the following rice crop (Olk et al, 2000). Gas production associated with straw incorporation such as CO$_2$, CH$_4$, C$_2$H$_2$, and H$_2$S is increased by incorporating straw in anaerobic soils (Neue and Scharpenseel, 1984). Moreover, costs and labor associated with straw incorporation may be limiting factors for farmers.

Removals of rice straw for other uses and burning of straw in other regions have been the tradition for a long time. According to Tanaka (1978) straw burning is the major method of disposal in many countries, particularly in Asia. The problems of burning straw are associated with atmospheric pollution and nutrient loss. The benefits are destruction of pests and saving labor and energy (Ponnamperuma, 1984). Straw burning has become increasing widespread in many countries such as India, where the use of combine harvesters have increased (Flinn and Marciano, 1984).

Although incorporation of rice straw has been reported to improve soil condition and plant performance through several manners, the economics of straw incorporation does not encourage farmers to regularly incorporate straw (Tanaka, 1974). Straw incorporation might be benefit in some regions where burning is prohibited and also where there no other use of rice straw such as livestock production.
2.4 Adverse Effects of Plant Residues

Plant residues can lead to negative effects on plant growth and production because of N immobilization and potential phytotoxic compounds. The adverse effects of substances from decomposing plant residues on poor growth and yield of crops have long been noted (Patrick et al., 1963). In anaerobic soils, microorganisms can produce a large variety of substances accumulated in the soils potentially toxic to plant roots (Lynch, 1976).

Therefore, incorporation of plant residue under anaerobic conditions can have adverse effects on the following crops such as rice and wheat (Cannell and Lynch, 1984). Takijima (1963) reported that the in strongly reduced soil conditions rice growth and root development often associated with growth-inhibiting substances. Tanaka and Yoshida (1970), De Datta (1981) and Dobermann and Fairhurst (2000) grouped physiological diseases of rice plants associated with submerged soil conditions by following symptoms: a) deficiency of nutrient elements such as N, P, K, Fe, Mn, and Si, b) toxicity of elements such as Fe, Mn, B, and Al, c) high salt injury, especially Na salts, and d) toxicity of substances produced and accumulated in the soil under anaerobic conditions such as sulfide, organic acids, and CO₂ (Cannell and Lynch, 1984).

Incorporation of crop residues under anaerobic condition can cause adverse effects on subsequent crops, particularly using the conservation tillage systems (Cannell, 1981). The operations of these tillage systems result in leaving plant residues on the soil surface or shallowly incorporated. When seed drills operate where plant residue are placed, seed and plant residues can be placed in close contact, particularly in fine textured-soil (which restricts oxygen diffusion).
Waterlogging or soil submergence can result in anaerobic conditions where plant roots and soil organisms when respiration demand for $O_2$ is faster than it can enter the soil by diffusion through air-filled pores (Currie, 1970). The rate of $O_2$ consumption depends on the biological activity and amount of organic matter, number of plant roots, and temperature of the soil (Cannell and Lynch, 1984). However, Kordan (1972) reported that rice seed can germinate under anaerobic conditions, but growth of the coleoptile, true leaves, and roots is abnormal. Since this growth stage coincide with the period of most rapid breakdown of organic matter, which phytotoxic substances may form, and it will likely be more injurious to plant growth (Cannell and Lynch, 1984). In addition, Harper and Lynch (1981) found that where plant residues are incorporated in soil, anaerobic decomposition is more likely and there is greater potential for production of phytotoxins as compared with an aerobic soil. The most common organic substances measured during anaerobic decomposition of organic matter in soil are aliphatic acids, phenolic acids, ethylene, carbon dioxide, and hydrogen sulfide (Cannell and Lynch, 1984).

Hydrogen sulfide ($H_2S$) can cause physiological disorders in rice roots grown on highly anaerobic flooded soils (Cartwright and Lee, 2004). Rice roots turn black and eventually die and rot, resulting in death of plant. If there is a large quantity of undecomposed crop residues present at the time of flooding, the reduction processes will increase or worsen this disorder. In the study of Gao et al. (2004), straw incorporation at the rate of 57.5 t ha$^{-1}$ (23 t acre$^{-1}$) induced sulfide toxicity symptoms and reduced rice yield. Sulfate additions which resulting in more sulfide production also reduced the number of tillers at the early stage.
Straw incorporation into soil can also influence methane production. Both amount of straw added and the method of incorporation, and water regime associated with the incorporation influence amount of methane produced. Methane production is greater during the first few weeks following permanent flooding (Sass et al., 1991). Straw incorporation associated with methane emissions also causes rice grain yields to decrease proportionately (Sass and Fisher, 1995).

2.5 pH CHEMISTRY OF FLOODED SOILS

Soil pH is one of the most important chemical properties of a soil. Soil pH governs to other chemical processes in the soil such as ion mobility, precipitation and dissolution equilibria, precipitation and dissolution kinetics, and oxidation-reduction equilibria (Bloom, 1999). Solubility of both elements and availability of plant nutrients vary with soil pH. Soil pH affects the chemistry and availability of plant nutrients and trace metals such as phosphorus, iron, manganese, copper, and zinc. The solubility of most toxic metals such as lead, cadmium, mercury and chromium are also affected by soil pH. In very acid soils, pH increases the availability of plant toxins such as aluminum, iron, and manganese. In contrast, these elements become deficiency in alkaline soils.

When an aerobic soil is submerged, the pH will approach neutrality (pH 7.0). The pH of alkaline soils declines and the pH of acid soils increases. The change in pH upon flooding may take a few days up to several weeks, depending on the soil type, organic matter sources and amounts, microbial population, temperature, and other soil chemical properties (Ponnampерuma, 1972; Snyder, 2002).

In alkaline soils, calcium carbonate (CaCO₃) is the major factor controlling soil reactions (1). Calcium carbonate may be present in high amounts in some soils, and when
this is the case, calcium carbonate controls soil reaction and keeping soil pH higher than neutral (Bohn et al., 1985)

\[ \text{CaCO}_3 - \text{CO}_2 - \text{H}_2\text{O} \quad \text{system} \] 

\[ \text{CaCO}_3 + 2\text{H}^+ \leftrightarrow \text{Ca}^{2+} + \text{H}_2\text{O} + \text{CO}_2 \] 

This reaction results in the neutralization of a strong acid, forming a weak acid (carbonic acid) (2). If the partial pressure of \( \text{CO}_2 \) is increased as a result of microbial activity and flooding which slows the removal of \( \text{CO}_2 \) in a gaseous form, then \( \text{CaCO}_3 \) may react to form bicarbonate (\( \text{HCO}_3^- \)).

\[ \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- \] 

The pH of solution of (3) is typically around 8.3 if the exchangeable sodium is low sodium when measured in the laboratory. Field pH values of calcareous soils are usually lower than 8.3 because root respiration and microbial decay of organic matter release \( \text{CO}_2 \), which must diffuse through soil pores to the atmosphere (Bohn et al., 1985). The pH values of submerges calcareous soils are lower than that of aerobic soils because of accumulation of \( \text{CO}_2 \) (Ponnamperuma, 1966).

In soils where sodium content is greater than 15 % of exchangeable sodium percentage on the cation exchange site, the major controlling reaction in sodic soils is sodium bicarbonate, water, and carbon dioxide system (4). Sodic soils are more common in the low rainfall regions because of the accumulation of sodium in soil profile. The pH chemistry of this system is similar to the calcium carbonate system (1).

\[ \text{Na}_2\text{CO}_3 - \text{CO}_2 - \text{H}_2\text{O} \] 

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In acid soils, the major reaction affecting soil pH is the oxidation and reduction of iron (5). In this system, flooded water plays significant role in controlling soil pH.

$$3\text{Fe(OH)}_3 + 3\text{H}^+ + e^- \leftrightarrow 3\text{Fe(OH)}_2 + 3\text{H}_2\text{O} \quad (5)$$

oxidized iron ($\text{Fe}^{3+}$)  reduced iron ($\text{Fe}^{2+}$)

Under flooded condition, $\text{H}^+$ is consumed by the reduction of iron resulting in an increase in pH of the system. In contrast, if the system is allowed to drain or become oxidized, the soil pH will revert to the original pH. In acid sulfate soils, the reduction and oxidation of sulfate is the major factor controlling soil pH, particularly the reduction of sulfate to sulfide contributes to raising pH of submerged soils at lower redox potentials (van Breemen, 1975). Although the increase in pH of acid soils is brought about by soil reduction, the fairly stable pH attained after a few weeks of submergence is also regulated by the partial pressure of CO$_2$ (Ponnamperuma, 1972).

However, certain soil chemical properties markedly influence the pattern of pH change (Ponnamperuma, 1972). If an acid soil is low in reducible iron and has low organic content, or is high in acid reserves, the pH may not attain a neutral value even after several weeks of submergence (Ponnamperuma, 1977). The increase in pH of an acid soil after submergence depends not only on the release of OH$^-$ ions and the consumption of H$^+$ ions but also on the ratio of H$^+$ ions consumed to electrons consumed (Bohn et al., 1985).

2.6 REDOX CHEMISTRY IN FLOODED SOILS

When a soil is flooded, the movement of oxygen and other gases from atmosphere to soil surface layer is restricted by the flooded water. The dissolved oxygen is quickly consumed by soil organisms and plant roots. Then the soil becomes anaerobic conditions
(Kyuma, 2004). For subsoil, ground water level is major controlling soil redox potentials. Under this anaerobic condition, flooded rice fields and occasionally flooded agricultural fields always have an oxidized surface layer overlying a reduced layer. The oxidation-reduction (redox) reactions occurring in this zone are driven by energy derived from microbial oxidation of organic matter. The thickness of oxidized layer is controlled by the rate of oxygen supply and rate of oxygen consumption by microorganisms and plant roots (Kyuma, 2004).

When an aerated soil is submerged, the redox potential (Eh) drops to a stable value from +200 to -300 mV depending on the soil type and other factors, but the Eh in the first few millimeters of the topsoil (oxidized layer) remains high potential at about +300 to +500 mV (Ponnamperuma, 1972). This unique redox potential can serve to distinguish a submerged soil from a well-drained soil. The rapid initial decrease of Eh is apparently due to the release of reducing substances accompanying oxygen depletion before manganese and iron oxide hydrates can mobilize their buffer capacity (Ponnamperuma, 1972). The change rate oxidation and reduction conditions in the soil also reflected the associated soil chemical and biological processes (Kyuma, 2004).

Patrick and Mahapatra (1968) subdivided soil Eh values associated with the reduction-oxidation states into four ranges: a) aerated (well-drained), Eh = +700 to +400 mV; b) moderately reduced, Eh = +400 to +200 mV; c) reduced, Eh = +200 to -100 mV; and d) highly reduced, Eh = -100 to – 300 mV. The course, rate, and magnitude of the Eh varies by the kind and amount of organic matter, the nature and content of electron acceptors, temperature, and the duration of submergence (Ponnamperuma, 1972).
Organic matter can increase the velocity of soil reduction but does not necessarily produce significantly lower ultimate potentials (Gambrell and Patrick, 1978).

However, the utilization of Eh as a tool for characterizing soil is limited because Eh varies with pH. Therefore, citing Eh values with considering the pH of the medium is more utilizable for forecasting the other related processes in the soils.

2.6.1 Eh of Soil, Soil Solution, and Soil Suspension

Not only do Eh vary due to the values being uncorrected for soil pH, Eh also vary considerably among measurements in soils, soil solution, and soil suspensions. Ponnamperuma, (1972) noted that at the early stages of reduction, soil Eh may be higher than solution Eh because of CO₂ effects. Rowell (1981) reported that in some conditions the Eh in soil suspension is found to be higher than in the extracted solution.

Solution Eh is quite different from soil Eh but suspension Eh seems to be similar to soil Eh. In suspension Eh, electrons are more accessible to the electrodes than in soil Eh. Yamane (1978) noted that Eh in the suspension is similar to solution Eh, but it can have quite different values. Although the soil Eh cannot have precise thermodynamic significance because of the heterogeneity problem, it is useful in describing the state of reduction of waterlogged soils (Ponnamperuma, 1972; Rowell, 1981).

2.6.2 Eh Changes Upon Draining

In flooded rice fields, surface water is often drained for a short time either by natural (in rainfed rice system) or by the intermittent irrigation practices. If the drainage is effective, the Eh value rapidly returns to original values or close to values before flooding (Kyuma, 2004). This change is controlled directly by the oxidation and reduction of iron. From the experiment of Motomura, 1969 (cited in Kyuma, 2004) found water-soluble Fe^{2+} only 5 % after 34 hours of drying as compared with those of flooding.
period. The rapid disappeared of Fe\textsuperscript{2+} also observed in the exchangeable form with less than 4 % during drying period as compared with those of flooding period. The reduction and oxidation of Fe\textsuperscript{2+} in soil can be observed in the in the field as gray or greenish gray soil coloration during flooding to yellowish gray or yellowish brown upon drying (Kyuma, 2004).

2.7 PLANT NUTRIENTS IN FLOODED SOILS

2.7.1 Macronutrients

2.7.1.1 Nitrogen

Nitrogen is the most yield-limiting element governing rice production, particularly in mineral rice soils. The efficiency of rice utilization of N fertilizer is directly related to other production factors such as, water management, rice growth stage, N source, and the chemical transformations of N after it is applied to the soil (Fageria et al., 2003). Soil nitrogen occurs primarily as organic forms in the soil. The breakdown of organic matter by mineralization process leading to the release of ammonium ions to the soil solution proceeds at a slower rate in a flooded soil than in a nonflooded soil (Ponnamperuma, 1972).

The mineralization process includes hydrolysis of proteins to polypeptides and amino acids, with subsequent resulting in the formation of ammonia. Most of the complex varieties of nitrogen containing-compounds are converted to ammonia (De Datta, 1981). The greater part of the nitrogen mineralized in flooded soil during a season appears as ammonia within two weeks after submergence if the temperature and other factors are favorable (Ponnamperuma, 1972; De Datta, 1981).

There are several factors that influence the denitrification process in the flooded soils. Those factors that affect the denitrification process are 1) internal factors or soil
factors, such as pH and pE, temperature, organic matter (amount and source), nitrate content and nitrification rate, submergence period, degree of puddling or aggregation, activity of microorganisms, O₂, and soil fertility, and 2) external factors or factors from outside, such as fertilizer nitrogen management, pesticide use and type of plants and others (De Datta, 1981).

The availability of nitrogen in flooded soils is higher than in aerated soils (Ponnamperuma, 1976; Dobermann and Fairhurst, 2000). Even though mineralization of organic matter in flooded soils is less than in aerated soils, the immobilization of nitrogen in flooded soils is less than the aerated soils resulting in greater nitrogen available (Borthakur and Mazunda, 1968).

Nitrogen losses from the flooded soils occur by several pathways such as denitrification, ammonia volatilization, leaching, and surface runoff. Freney et al. (1990) reported that the significant fertilizer-N losses from the irrigated flooded rice fields are usually attributed to ammonia volatilization and denitrification.

2.7.1.2 Phosphorus

Phosphorus deficiency is the second most important nutritional disorder of lowland rice, especially in the highly weathered acidic soils of the tropics that contain large quantities of Al and Fe oxides (Wells et al., 1993; Baligar and Fageria, 1997; Fageria et al., 1997). Phosphorus content of most mineral soils ranges between 200 to 5,000 mg kg⁻¹ with an average of 600 mg kg⁻¹ (Lindsay, 1979). Soil P exists in both organic and inorganic forms. The inorganic form is more important under waterlogged conditions.
The transformations and chemistry of P in flooded soil have been reviewed by Ponnamperuma (1972) and Sanyal and De Datta (1991). Khan and Mandal (1973) reported that rice soils contained organic-P about 34.7 % of the total-P, and among the inorganic-P fractions were 27.8 % Fe-P, 7.2 % Al-P, 46.6 % Ca-P, and 16.2 % reductant soluble Fe-P and 2.2% occluded Al-P. Usually, iron phosphate (Fe-P) is reported to be the most predominant inorganic phosphate in rice soils (Chang and Chu 1961; Mahapatra and Patrick, 1969). It has been found that large amounts of both indigenous and fertilized phosphates in the form of phosphate ions, calcium phosphate, and aluminum phosphate are subsequently converted to iron phosphate (Chang and Chu, 1961; Srivastava and Pathak, 1972). In a study on phosphorus fractionation in a soil which had received super phosphate application for 31 years, Chang and Chu (1961) found that the phosphate was retained mostly as iron phosphate, following by aluminum phosphate, and calcium phosphate.

In general, submergence increases availability of P to plants (Ponnamperuma, 1977). The two main reasons are: 1) the reduction of insoluble ferric phosphate to soluble ferrous phosphate, and 2) the reduction of iron oxide, which releases the occluded phosphate (Patrick and Mahapatra, 1968). Patrick (1993) reported that the alternate flooding and drying increases the amount of phosphorus in the ferric phosphate and reductant-soluble (RS-P) occluded fractions at the expense of the soluble and aluminum phosphate fractions. Moreover, Fujiwara (1950) noted that hydrolysis of aluminum and iron phosphates may also enhance phosphorus in flooded soils. Willett (1986, 1989) reported that P availability increases after flooding from the 1) reductive dissolution of
ferric oxides; 2) the liberation of sorbed and RS-P; 3) change in soil pH affecting the solubility of Fe-P, Al-P, and Ca-P; and 4) the desorption of surface P.

Phosphorus is not directly involved in oxidation-reduction reactions, but because of its reactivity with a number of redox elements, its behavior is significantly affected by movement of soil solution. Perhaps the most important effect of the anaerobic condition on phosphate is the increased availability of P to wetland rice (Patrick and Reddy, 1978).

As mentioned above, phosphorus solubility is also affected by the soil pH. An increase in pH, considered without regard to redox conditions will increase the solubility of ferric phosphate and aluminum phosphate but will decrease the solubility of calcium phosphate (Lindsay and Moreno, 1960), and a decrease in pH favors the solubility of calcium phosphate as well as ferrous and manganous phosphate (Stumm and Morgan, 1970). Thus the solubility of P in soil tends to be maximal in the pH range of 6 to 7 (Brady, 1974). However, under reducing conditions, maximum phosphate solubility occurs under low pH conditions (Patrick et al., 1973). He also found that either low Eh or low pH the solubility of P increases to some extent but the combination of low Eh and low pH enhanced P solubility considerably. The increase in pH of acid soils and the decrease in pH of calcareous and sodic soils due to submergence increase the availability of phosphorus (Ponnamperuma, 1978).

Although the mobility of phosphate in flooded soils is greater than that in upland soils, the soluble phosphate is largely fixed or retained when applied to wetland soils (Chang, 1976). Phosphorus fixation is found to be rapid in acid and neutral soils as compared with in alkaline soils (De Datta et al., 1966). Phosphorus fixation is the most
Rapid process in acid sulfate soils (van Breemen and Pons, 1978; Attanandana and Vacharotayan, 1981; Attanandana, 1982).

2.7.1.3 Potassium

Rice does not generally respond to K fertilization at the same level as N or P. Many soils used in continuous rice production can be cropped for extended periods without applying supplemental K to maintain crop production (Dobermann et al., 1996). Direct K fertilization of rice has produced grain yield increases ranging from 0-47% (Dobermann et al., 1996). However, on some soils, K deficiency of rice may occur if rice and rotation crops are grown without regular applications of K fertilizer to replace the K removed by the harvested crops (Fageria et al., 2003). Recently, K deficiency was recognized as an annual problem on many soils as rice and rotation crop yields have increased, soils have been depleted of K, and production practices have changed (Slaton et al., 1995; Williams and Smith, 2001).

In highly weathered soils, the total soil K content may be quite low because of K deficient parent materials and climate. High rainfall and warm temperatures in tropical rice growing area have accelerated the release and leaching of soil K over time (Tisdale et al., 1985). Leaching is a significant problem in the humid tropical regions, particularly acid soils with low cation exchangeable capacity. Liming an acid soil to raise its pH can reduce leaching losses of K because of the complementary ion effect and increasing soil cation exchangeable capacity (Brady and Weil, 1996).

In flooded soil, concentration of K increases after flooding. Soil reduction also increases the concentration of Fe, Mn and other cations, which displace K from the cation exchange sites into the soil solution (Dobermann and Fairhurst, 2000). The result is an
increase of K in the soil solution, where K can either absorbed by rice plants or leached to depths below the rice root system (Patrick et al., 1986; Wells et al., 1993). In addition, flooding of dry lowland rice soils containing 2:1 layer clay minerals may increase K fixation and reduce the solution concentration (Dobermann and Fairhurst, 2000).

2.7.1.4 Sulfur

Sulfur is involved in chlorophyll production, hormones, amino acid and protein synthesis in plant (Dobermann and Fairhurst, 2000). In rice plant, sulfur deficiency results in yellowing of the whole plant, and chlorosis can be seen in young leaves with the tips may become necrotic. Severe deficiency of S in rice is also reducing grain yield. In most lowland rice soils, S supply is greater or similar to the amount of S removal by plant (Dobermann and Fairhurst, 2000).

Sulfur is referred to a secondary element. Sulfur deficiency has been reported in the most rice producing regions of the world including Indonesia, India, Brazil, Bangladesh, Thailand, and the USA (De Datta, 1981; Wells et al., 1993). Blair et al (1978) suggested that the low S content of most tropical soils was the primary cause of S deficiency.

In flooded soils, sulfate reduction is found to take place at lower redox potentials. Connell (1966) and Connell and Patrick (1968, 1969) reported that the critical Eh for the inception of sulfate reduction was about -150 mV. Harter and McLean (1965) found that sulfide contents in the solid increased rapidly at the redox potential below -75 mV. Postgate (1959) proposed that to stimulate the microbial reduction of sulfate to sulfide the soil Eh should be about -200 mV. He also demonstrated that the addition of a solution containing 15 mg kg$^{-1}$ of H$_2$S resulted in lowered Eh to -200 mV. In reverse, sulfide is
rapidly oxidized to sulfate when it is exposed to air. Connell (1966) showed that a soil containing 120 mg kg\(^{-1}\) of total sulfide decreased to 5 mg kg\(^{-1}\) after it exposed to air for 2 hours. The rate of sulfate reduction in submerged soils also depends on other soil properties (Ponnampерuma, 1972).

The reduction of sulfate to sulfide in flooded soils is normally occurring at localized even in the same horizons (Ponnampерuma, 1978). Even though the bulk of sulfate persists for several months after flooding in most flooded acid sulfate soils, significant amounts of dissolved sulfide may form within weeks (Ayotade, 1977).

In reduced soils when sulfate is transformed to sulfide, usually the bulk of sulfide (mainly FeS) is present in the solid phase, but even low concentrations of dissolved sulfide (> 0.1 mg kg\(^{-1}\)) may be harmful to rice (Mitsui, 1955). Soluble Mn in reduced soils has been noted to be capable of precipitating sulfide as MnS. Connell and Patrick (1969) reported that reduced Mn was less efficient than reduced Fe in precipitating H\(_2\)S, because FeS is more insoluble than MnS. Takijima et al. (1962) noted that soils high in iron oxides produced very little free H\(_2\)S with this soluble sulfide content considered insignificant (Takijima et al., 1962). Ponnampерuma (1965) stated that in soils abundant in Fe, the presence of Fe in the soil solution keeps the concentration of H\(_2\)S below \(10^{-8}\) M, even though soluble Fe\(^{2+}\) was present.

2.7.2 Micronutrients

2.7.2.1 Iron

Iron chemistry of flooded soils is dominant more than any other elements. Solubility of Fe increases under anaerobic condition as the result of Fe\(^{3+}\) reduced to soluble Fe\(^{2+}\) during organic matter decomposition (Dobermann and Fairhurst, 2000). The reduction and oxidation of iron compounds are cyclic when the soils undergo seasonal
flooding and draining. Ponnamperuma (1976) found that the concentration of Fe$^{2+}$ of flooded soils increased to a peak ranging from 0.1 to 600 mg kg$^{-1}$ for several soils shortly after submergence and then declined. The reoxidation of the reduced iron enables its oxidized form to buffer the redox potential at intermediate Eh value during the flooding period (Patrick and Reddy, 1978).

The reduction of iron appears to be mainly a microbial process (Bloomfield, 1951), although direct reduction coupled with respiration may be involved (Kamura et al., 1963). The reduction of Fe$^{3+}$ is important in providing available Fe$^{2+}$ for the nutritional requirements for rice plants. The rate of reduction and amount of Fe$^{2+}$ produced also depend on active Fe, temperature, Eh, pH, and organic matter (Dobermann and Fairhurst, 2000). However, in some conditions where soil pH and Eh are low the high concentration of Fe$^{2+}$ can cause toxicity to the plant (Ponnamperuma, 1972).

Ponnamperuma (1978) noted that the increase in concentration of water-soluble Fe$^{2+}$ can displace K$^+$, Na$^+$, NH$_4^+$, Ca$^{2+}$, and Mg$^{2+}$ from exchange sites. This cations displaced enhance the lost of those ions by leaching or by surface runoff under flooded condition. Kawaguchi and Kawachi (1969) claimed that an increase of Ca levels in flooded soils was due to the displacement of Ca$^{2+}$ by Fe$^{2+}$. Ferrous ions occupied considerable parts of exchange sites, but after air-drying, exchangeable Fe$^{2+}$ disappeared while Al$^{3+}$ and H$^+$ increased (Ponnamperuma, 1978).

Gotoh and Patrick (1974) reported that an increase in water-soluble and exchangeable iron were favored in the low redox potential and low pH. They also noted that the distribution between water-soluble and exchangeable iron fractions was highly pH dependent. Addition of fresh organic matter into the soils hastens iron reduction and
the peak in Fe\textsuperscript{2+} followed a decline in Fe\textsuperscript{2+} (IRRI, 1976). The concentration of water-soluble iron seems to be highest in acid sulfate soils because of high amount of active iron oxides. In neutral to alkaline soils, water-soluble Fe\textsuperscript{2+} increases steadily to the final values of 5 – 50 mg kg\textsuperscript{-1} (IRRI, 1965). Water-soluble Fe\textsuperscript{2+} has been reported to be lowest in alkaline soils, particularly under low in organic matter content (Ponnambepuruma, 1978). Low temperature retards the peak of water-soluble Fe\textsuperscript{2+} and broadens the area under it, but does not prevent a later increase in concentration (Cho and Ponnambepuruma, 1971). In high organic matter soil but low in iron, the peak of water-soluble Fe\textsuperscript{2+} concentrations persist for several months (Ponnambepuruma, 1972).

In general, soil solution Fe concentrations are high in flooded soils because of the anaerobic soil conditions, but rice is well adapted to soil environments and is normally able to regulate Fe uptake (Fageria et al., 2003). Iron deficiency reduces seedling dry matter production, leaf chlorophyll content, panicle number per unit area, and grain yield (Snyder and Jones, 1988). Iron toxicity is related to multiple nutritional stresses (Dobermann and Fairhurst). Severe iron toxicity can cause significant rice yield reductions (Genon et al., 1994).

2.7.2.2 Manganese

Like Iron, Manganese is a redox element and widely distributed in soils, but largely in the unavailable form to plants. Manganese oxides are the major form of the manganese minerals in soil. Manganese has six valence states; 0, +2, +3, +4, +6, and +7. Mn\textsuperscript{2+}, Mn\textsuperscript{3+}, and Mn\textsuperscript{4+} are the common valence states found in most soils with Mn\textsuperscript{2+} being the primary form absorbed by plants (Fageria et al., 2003). The concentration of Mn\textsuperscript{2+} in the soil is affected by soil pH, redox status, moisture tension, microbial activity,
and temperature (Mikkelsen and Kuo, 1976). Its solubility decreases 100 fold as increasing one unit of pH (Barber, 1995; Tisdale et al., 1985). In submerged soils Mn$^{4+}$ is reduced to Mn$^{2+}$ after depleting of NO$_3^-$.

The transformations of manganese under submergence are thought to be similar to those of iron. The oxidized forms of soil manganese are highly insoluble and exist primarily as oxides of various degree of reactivity, while the reduced divalent ion in the soil solution is more soluble. The availability of Mn to plants is largely dependent on the soluble forms of Mn in the soil. All forms are in dynamic equilibrium with each other and the form of Mn, which predominates at any one time, is dependent on other soil properties (Lovley, 1995).

Turner (1967) found that low pH values are favorable for reduction of Mn while an increasing pH above 5.5 the conditions are favorable for oxidation. Bromfield and David (1976) found that the rate of oxidation was highly pH dependent, with the maximum rate occurring at pH 6.5 and no oxidation occurred below pH 5.0 and above pH 7.9.

Patrick and Reddy (1978) noted that the concentration of Mn$^{2+}$ in soil suspension is highly dependent on both pH and redox potential, except at pH values below 5.0 where pH alone can control solubility. Under controlled Eh-pH in stirred suspension, Gotoh and Patrick (1972) found that at pH 5.0 the release of water-soluble Mn occurred at Eh of +700 mV.

After reduction, the Mn$^{2+}$ ions can remain in solution or be adsorbed on the exchange complex if the pH is below neutral. For flooded soils with near-neutral pH, the reduced Mn$^{2+}$ can also precipitate as MnCO$_3$ (Ponnampерuma et al., 1969) or as oxides.
and hydroxides of Mn (II) (Patrick and Reddy, 1978). Ponnamperuma (1965) reported that water soluble Mn\(^{2+}\) increase sharply during the first few weeks of submergence and then declined. Ponnamperuma et al (1969) claimed that the steep declined in concentration after the peak was due to precipitation of MnCO\(_3\). Patrick and Turner (1968) suggested a decrease of dissolved Mn was due to the expense of water-soluble or exchangeable Mn. Gotoh and Patrick (1972) also noted that both low pH and low Eh were found to increase water-soluble Mn at the expense of exchangeable form.

Ponnamperuma (1972) commented that exchangeable Mn maybe forms MnCO\(_3\) under ammonium acetate extraction. In reduced soils, Manganese Mn may precipitate with other anions such as phosphate, silicate, sulfide, and hydroxide (Huang and Keller, 1972). Thus, the extraction of exchangeable Mn with the extractant pH below 5.0 may include of the reducible Mn, oxidizable Mn, and residual Mn.

2.7.2.3 Zinc

Zn deficiency in plants has been reported in many parts of the world (Mandal et al., 2000; Fageria, 2001). In tropical Asian countries, Zn deficiency has been reported to be more serious problems in rice fields. For example, De Datta (1981) reported that Zn deficiency is the second most nutritional limiting grain yield of lowland rice in the Philippines. Japan used to have Zn deficiency, known as “akagare type II” (Kyuma, 2004). Converting of upland to use as lowland rice fields is also causing Zn deficiency (Kyuma, 2004). The availability of Zn is influenced by a number of soil characteristics such as soil pH; organic matter; CaCO\(_3\); cation exchange capacity; clay mineralogy and content; and the quantity and types of Fe, Al, and Mn oxides (Harter, 1991; Hazra and Mandal, 1996; Singh et al., 1997).
Under submerged condition, Zn availability is decreased because of the reduction in its solubility (Dobermann and Fairhurst, 2000). Mikkelsen and Kuo (1976) note that the concentration of Zn in the soil solution generally decreases with time after flooding but the concentration may increase temporarily after flooding. The uptake, translocation, metabolism, and plant use of Zn is inhibited by high P availability, particularly with the high rate of P fertilizer applications (Lindsay, 1979).

Dobermann and Fairhurst (2000) indicates that the critical soil Zn concentration for rice are 0.6 for 1N NH$_4$-acetate, pH 4.8, 0.8 mg Zn kg$^{-1}$ for DTPA, 1.0 mg Zn kg$^{-1}$ for 0.5 N HCl, 1.5 mg Zn kg$^{-1}$ for EDTA, mg Zn kg$^{-1}$ for 0.1 N HCl. Sims and Johnson (1991) also noted that the critical concentration of soil Zn in most crops ranged between 0.5 to 2.0 mg Zn kg$^{-1}$ for DTPA and 0.5-3.0 mg Zn kg$^{-1}$ for Mehlich 1. In lowland rice, Fageria (1989) reported that 1.0 mg Zn kg$^{-1}$ of soil extracted by the Mehlich 1 method was the critical concentration. In Arkansas, and Louisiana Zn fertilizer recommendations for flooded rice are common with based on soil pH, texture, and Mehlich 3 extractable Zn (Wilson et al., 2001). For rice grown on silt and sandy loam soils having a pH greater than 6.0 and Mehlich 3 extractable Zn less than 3.5 mg Zn kg$^{-1}$, Zinc fertilizer is recommended (Fageria et al., 2003).

2.8 GREENHOUSE GASES AND GLOBAL WARMING

The average global temperature is determined by the equilibrium between incoming energy from the sun and outgoing energy as heat from the earth. Greenhouse gases produce a warming effect by allowing incoming solar radiant energy to penetrate to the Earth’s surface. Part of the outgoing infrared radiation is trapped by greenhouse gases in the lower atmosphere and then re-emitted. This process is referred to the “greenhouse
effect”, which adds to the net energy input of the lower atmosphere and thus leads to an increase global temperature (“global warming”) (IPCC, 1990).

The concentration of greenhouse gases is increasing since pre-industrial times due to human activities. The key greenhouse gases responsible for the enhanced greenhouse effect, carbon dioxide (CO\textsubscript{2}), methane (CH\textsubscript{4}), nitrous oxide (N\textsubscript{2}O) and the manmade chlorofluorocarbons (CFC’s) are associated with economic activities and food production (IPCC, 1996; Denier van der Gon, 1996).

Increasing rate of greenhouse gases emission to the atmosphere is likely to hasten the rate of climate change. According to EPA (2000), since the late 19\textsuperscript{th} century the average temperatures of the Earth’s surface have increased 0.3 – 0.6 °C. In The 20\textsuperscript{th} century, 1998 was the warmest year on record resulting in a decrease in the amount of snow in the Northern Hemisphere and amount of floating ice in the Arctic Ocean. Global sea level has risen 10-20 cm over the past century. Worldwide precipitation over land has increased by about one percent (EPA, 2000).

2.8.1 Methane Formation

Methane (CH\textsubscript{4}) is produced by strict anaerobic bacteria (methanogens) as the terminal step of the anaerobic degradation of organic matter (Neue, 1993; Denier van der Gon, 1996). CO\textsubscript{2} and CH\textsubscript{4} are the most important gaseous end-product of organic matter decomposition under anaerobic conditions (Acharya, 1935a; 1935b). The rate of CO\textsubscript{2} and CH\textsubscript{4} produced in soil is controlled by several factors such as organic materials, temperature, pH and other soil factors. For example, Wang et al. (1993) reported that methanogenic bacteria can metabolize only in the absence of free oxygen and at redox potentials less than -150 mV. In alkaline or calcareous soils (high pH soils) methane
production may start faster than in neutral soils after flooding (Neue, 1993).

Ponnamperuma (1987) found that increasing temperature from 20 to 35 °C of straw incorporation significantly increased methane production. In wetland rice soils, methane is a largely produced by transmethylation of acetic acid and by the reduction of carbon dioxide (Takai, 1970).

There are two major pathways that produce methane in submerged soils (Neue and Scharpenseel, 1984; Papen and Rennenberg, 1990; Takai, 1970):

1. Reduction of CO$_2$ with H$_2$ (deriving from organic compound)

   \[
   \text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}
   \]

2. Decarboxylation (transmethylation) of acetic acid

   \[
   \text{CH}_3\text{COOH} \rightarrow \text{CH}_4 + \text{CO}_2
   \]

Methane production in rice soils generally increases during the cropping season (Schutz et al., 1989). The fluctuations of the soil temperature and the rice plant-growing activities importantly contribute to the diurnal fluctuations in methane emission (Wang et al., 1993). Rennenberg et al. (1992) noted that both quantity and quality of the available carbon source either from amended organic matter or root exudates significantly influences the methane production. The seasonal variations are explained by the change in available substrate, the water regime, and other factors of the rice fields (Minami and Neue, 1994).

2.8.2 Wetland Rice Fields as a Source of Methane

Most rice production is in flooded fields where the soils become strongly anaerobic resulting in methane generation. It is estimated that methane contributes about 20% of the greenhouse gases effect involved in global warming. Flooded rice is believed
to contribute one-fourth of the total methane emission, or accounted for 5% of the overall increase in global warming (Wang and Patrick, 1996).

The potential for rice fields to emit CH$_4$ has long been noted, but comprehensive field measurements begin only in the early 1980s (Neue, 1993). As mentioned earlier, methane emission from rice fields is controlled by several factors such as carbon source, temperature, soil moisture regime, soil redox potential, rice variety, fertilizer, and cultural practices. These factors contribute to the variation in recent estimate of CH$_4$ emission from rice fields, for example, 95 Tg year$^{-1}$ (Khalil and Rasmussen, 1983); 70-170 Tg year$^{-1}$ (Holzapfel-Pschorn and Seiler, 1986; Schutz and Seiler, 1989); 53-114 Tg year$^{-1}$ (Bouwman, 1990); 22-73 Tg year$^{-1}$ (Yagi and Minami, 1990); 20-100 Tg year$^{-1}$ (IPCC, 1992; IPCC, 1994); 50 Tg year$^{-1}$ (Neue, 1993); 60-110 Tg year$^{-1}$ (Wang et al., 1994); 100 Tg year$^{-1}$ (Reeburg and Crill, 1996); 20-50 Tg year$^{-1}$ (Neue and Sass, 1998). The uncertainties of an amount of methane emission are also related to unstable environmental conditions associated with growing rice, and difference in experimental approaches, and flux measurements (Wassmann, et al. 2000).

Rice fields are one of the most important sources of atmospheric CH$_4$ accounting for 15-20% of the world’s total anthropogenic CH$_4$ emission (Neue and Sass, 1998). Methane emissions from flooded rice fields during the entire growing season generally show three distinct seasonal peaks (Schutz et al., 1989). The first peak develops shortly after flooding, the second during the vegetative stage of the rice plant, and the third during the grain filling and maturity stage (Neue and Sass 1994).

In irrigated rice fields, water supply is controlled and the fields normally are submerged throughout the growing season for controlling weeds, diseases, and for
obtaining optimum yields (Neue, 1993). Upon flooding of rice, anaerobic decomposition of organic matter occurs. Methane is a major end product of anaerobic decomposition of soil organic matter and can escape to the atmosphere by three pathways; ebullition, diffusion through surface layers of the soil and the floodwater, and through the aerenchyma of the rice plants (Aulakh et al., 2001). A significant portion of the CH$_4$ produced under flooded conditions is oxidized by methane-oxidizing bacteria (methanotrophs) within the soil and overlying water before escaping to the atmosphere (Neue, 1993). The oxidation of CH$_4$ in the root rhizosphere is also influenced by the ability of the rice plant to transport O$_2$ from the atmosphere to the soil via its aerenchyma tissues (Aulakh et al., 2001).

2.8.3 Methane and Nitrous Oxide Emission from Rice Field

Among the greenhouse gases, methane ranks second to carbon dioxide in importance (IPCC, 1996). The total annual global of atmospheric methane is estimated to be 500 teragrams (Tg) (IAEA, 1992), with an uncertainty between 10 and 20 % (Khalil, 1992). The rapid increase of methane concentrations in the atmosphere from 0.8 ppmv (ppm based on volume) in pre-industrial times to present time 1.78 ppmv is apparently linked to human activity (Khalil et al., 1993; Raynaud et al., 1993).

Yagi and Minami (1990) reported that annual emission rates from plots receiving 6 t ha$^{-1}$ of rice straw in addition to mineral fertilizer increased approximately 2 to 3 fold as compared with the mineral fertilizer plots. The early flush of CH$_4$ emission resulted from the decomposition of soil organic matter and added organic materials such as rice straw. Alberto et al. (1996) reported that straw incorporation increased dissolved CH$_4$ approximately ten fold. Corton et al. (2000) also found that CH$_4$ emission was low during
early stages and increased at the later stages of rice growth. At the later stages, root exudates and the decaying roots become the major carbon source for CH$_4$ production (Alberto et al., 1996).

2.9 MITIGATION OPTIONS TO REDUCE METHANE EMISSION

Since the major factor governing methane production is anaerobic condition which is common in wetland rice production. The most effective mitigation option for reducing methane emission would be to keep rice fields submerged during the cropping season for a short time as possible. Only half of the global lowland rice fields are grown under irrigated conditions (FAO, 2001). The rest of rice grown is under rainfed system which the fields are flooded naturally during the rainy season. Controlling water in the rice fields is practicable only in the irrigated rice ecosystems. Detail of water management in rice field is discussed in the following section. However in addition to water management, there are several other factors such as rice variety, fertilizer application, soil characteristics and other farm management practices which also influence methane production and emission from rice fields. Mitigation options must include integration of all feasible management practices in order to achieve both reduced methane emission and increased sustainable production of rice (Neue, 1993).

2.9.1 Water Management to Reduce Methane Emission

Increasing rate of water percolation in rice soil would be an important strategy for allowing oxygen to enter the reduced soil layer and decrease methane production (Neue, 1993). The limitation of this mitigation practice is only feasible where the water supply and drainage can be controlled. This technique required more water and may enhance nutrients loss through leaching (Neue, 1993). Significant quantities of methane may also
be leached with time and subsequently emitted elsewhere to the atmosphere (Kimura, 1992). In some rainfed areas, where the amount of rain is very low or during drought year, water is too valuable to be drained. Intermittent wetting and drying the rice fields and limiting irrigation will increase oxygen supply to the soil which would result in increase in methane oxidation and a decrease in methane formation. Intermittent aeration, however, may increase losses of gaseous nitrogen through nitrification and denitrification processes (Neue, 1993).

Reducing the amount of water-use for wetland rice production is still controversial since there are critical issues associated with yield loss. De Datta (1981) noted that water stress at any growth stage reduces rice yield. Soil moisture content of -50 kPa (slightly above field capacity) may reduce rice grain yield by 20-25% as compared to continually flooded treatments. Rice is most sensitive to water stress during the reproductive stage. Water shortage at this growth stage can cause yield loss by lowering sterility (Yoshida, 1981). Water deficit during the vegetative stage can reduce plant height, tiller number, and leaf area, and grain yields if plants do not have adequate time to recover before flowering (Castillo et al. 1992).

Borell et al. (1991) reported that intermittent drying or keeping soils only saturated during the growing season significantly lowers rice yields in most tropical rice fields. The duration of a moisture stress is also important because extended duration of moisture stress may cause plant injuries. Draining the flooded rice field for short periods at the end of the tillering stage can improve wetland rice yields if followed by flooding (Neue, 1993).
Water management techniques are feasible in mitigating methane emission from rice fields. However, reducing water use in wetland rice fields can be the limiting factor in growth and grain yield. Thus feasible water management practices that reduce methane emissions without adverse effects on rice growth and grain yield are desirable.

2.9.2 Rice Cultivars

Methane transport through rice plant is a major pathway for methane emission to the atmosphere in wetland rice cultivation. Approximately 90% of methane released from rice fields to atmosphere over a cropping season is transported via rice plants (Cicerone and Shetter, 1981; Holzapfel-Pschorn et al., 1986). Like other wetland plants, rice produces aerenchyma to transport oxygen from atmosphere to rhizosphere under anaerobic condition. Aerenchyma also serves as connector allowing methane produced in paddy soils to be emitted to the atmosphere. Neue (1993) noted that the flux of gases in the aerenchyma depends on concentration gradients and diffusion coefficients of roots and internal structure. Aulakh et al. (2001) stated that rice cultivars with different physiological adaptation different in potential to transport methane from the root to atmosphere. Rice cultivars usually vary in the number of tillers per hill, the root mass, the rooting pattern, leaf size and pattern, and height. Kimura (1992) reported that the older tillers within a single hill released greater amount of methane to the atmosphere as compared to the younger plants. Sass et al. (1990) found positive correlations between root biomass and methane emission. Root exudates and root decay at the later rice growth stages are the major carbon sources for methane production and emission from rice fields.

2.9.3 Fertilization and Other Cultivation Practices

Fertilizers are used broadly in wetland rice production to increase plant growth and grain yield. Fertilization has been reported to both directly and indirectly influence
methane emission. Conrad and Rothfuss (1991) reported that application of ammonium to floodwater resulted in increased methane emission. Lindau et al. (1993) found that application of sodium sulfate (Na$_2$SO$_4$) resulting in reduced methane emission as compared to ammonium sulfate ((NH$_4$)$_2$SO$_4$). Urea is the dominant fertilizer N source use in lowland rice production. Ammonium N is generated directly from the hydrolysis of urea in flooded water. Most farmers apply nitrogen fertilizer in two or three split applications. The first split application is usually applied during land preparation or at the early growth stage and the last application at the later growth stages under standing water (Neue et al., 1995). These fertilization practices can enhance both methane and nitrous oxide emission from wetland rice cultivation.

Since methane is one of the end products of organic matter decomposition in submerged soils (Ponnamperuma, 1972), application of organic materials to wetland rice soils has been reported to increase methane production and emission (Schutz et al., 1989; Yagi and Minami, 1990). As mentioned in previous sections, organic matter provides carbon sources which enhance soil reduction or anaerobic conditions. Both quality and quantity of organic materials influence methane formation (Neue, 1993).

To significantly reduce methane emission from wetland rice fields, it will be necessary to integrate all farm management practices as described above. Water management, use of selected rice cultivars, fertilizer types, particularly organic fertilizers and fertilization techniques must be considered. Those factors can potentially decrease methane emission from wetland rice cultivation but they also govern rice yield and the improper use of these management factors can cause yield reduction. Thus further studies are needed to evaluate the combined use of the various factors for reducing methane emission without yield loss.
CHAPTER 3

SOIL REDOX POTENTIAL, ORGANIC MATTER, AND RICE GROWTH IN COMMERCIAL FARMS: FIELD EXPERIMENT

3.1 INTRODUCTION

Commercial rice farms located near Lake Charles and North of Crowley, Louisiana, identified problems associated with abnormal growth of rice seedling, reduced stand density and certain death in their fields. Soil samples were collected from the areas either identified by poor rice growth or areas where there was normal seedling development. The soil samples analyzed at the LSU Wetland Biogeochemistry Institute indicated that the soil samples from the areas of poor plant survival contained high level of organic matter.

The adverse effects of substances from decomposing plant residues on poor growth and yield of rice and many other crops have long been documented (Patrick et al., 1963; McCalla and Haskins, 1964). In aerobic soils, microorganisms can produce a range of substances accumulated in the soils potentially toxic to plant roots (Lynch, 1976). Therefore, incorporation of plant residue under anaerobic conditions can have adverse effects on the following crops such as rice and wheat (Cannell and Lynch, 1984). In high organic matter wetland rice soils, symptoms associated with poor rice root systems often have been observed in the presence of growth-inhibiting substances under extremely reduced conditions (Takijima, 1963). Poor rice growth in submerged soils has also often been related to the chemical processes occurring in a strongly reducing soil conditions (Cannell and Lynch, 1984).

conditions by following symptoms: a) deficiency of nutrient elements such as N, P, K, Fe, Mn, and Si, b) toxicity of elements such as Fe, Mn, B, and Al, c) high salt injury, especially Na salts, and d) toxicity of substances produced and accumulated in the soil under anaerobic conditions such as sulfide, organic acids, and CO₂ (Cannell and Lynch, 1984).

When plant residues are incorporated, anaerobic decomposition is more likely to occur in soil. But when plant residues are left on the soil surface or under aerobic soil conditions, degradation is slower, which results in less potential for phytotoxic effects on plants (Harper and Lynch, 1981). In many conditions, there is no clear or quantifiable links between the observed plant growth effects and the substances in the soil environment to which the effects are associated. This can be due to the difficulties in measuring the particular substance, or only a limited number of substances found in the soil environment (Cannell and Lynch, 1984).

Aliphatic acids, phenolic acids, ethylene, carbon dioxide, and hydrogen sulfide are the major organic substances. The toxic effects of aliphatic acids on rice growth have been widely studied. Takijima (1964) reported that rice seedlings died within 3 weeks when grow in culture solution containing 6 mM acetic acid. Rao and Mikkelsen (1977b) found that 14-day-old seedlings died within 2-3 days when grown in solutions with 10 mM concentrations of acetic, propionic, or butyric acid. There is no unequivocal evidence to support phytotoxic effects of aliphatic acids in tillering inhibition, reduced straw weight, and grain yield (Cannell and Lynch, 1984).

Chandramohan et al. (1973) found that 0.1 M cinnamic acid depressed shoot growth of rice seedlings in solution culture. Ethylene generated within the tissues and
trapped by water films may accelerate rice stem elongation of the mesocotyl (Suge, 1971) and the coleoptile (Ku et al., 1970), enhancing that submerged shoots quickly reach the surface of the water. Ethylene is also involved in the mechanism of regulation of internode elongation in floating rice (Metraux and Kende, 1982). CO\textsubscript{2} may adversely affect the growth of some species under highly reduction conditions. However, Rao and Mikkelsen (1977a) reported that high concentrations of CO\textsubscript{2} injuring plants may be due to the effects of excluding O\textsubscript{2} by the gassing procedure. Hydrogen sulfide has also been noted as a general cell poison, inhibiting enzymes and the uptake of nutrients (Cannell and Lynch, 1984). Tanaka et al. (1968) reported that hydrogen sulfide may also contribute to Fe toxicity in rice, because the production of the gas and FeS in flooded soil under highly reduced conditions results in lowering the oxidizing power of rice roots. Gao et al. (2004) reported that elevated levels of straw incorporation may have caused sulfide toxicity effects on rice plants. Hydrogen sulfide is a strong inhibitor of aerobic respiration after entering the roots, causing nutritional imbalance and physiological disorders (Kumazawa, 1984). The most observable symptoms of sulfide toxicity are blackened roots, and reduced height and number of tillers (Cartwright and Lee, 2004).

Based on the results of soil analysis of the three farms, we initiated field experiments in 2002, to monitor and collect data of the redox status, plant growth, selected soil chemical and physical properties, and data. These field experiments were established in three commercial rice farms. Two fields located near Lake Charles and one North of Crowley, Louisiana.

The objectives of this field investigation were i) to identify soil parameter contributing to poor seedling development and plant growth, ii) to monitor soil redox
potential as related to organic matter, pH, nutrients available and plant growth, and iii) to identify management practices for remediation the poor rice growth in problem soils.

3.2 MATERIALS AND METHODS

3.2.1 Sites Description

Locations of the three commercial farms with problem rice soil are shown in Fig. 3.1.

a) Farm 1, a farm located in the Lake Charles area. Soil at this site was classified as Crowley series (Soil Survey, 1988). Soil surface was slightly shallow approximately 10 cm in the area near the bund and 15 cm in the middle of the field. Farmer used water from a canal in irrigating the rice cultivation at the site. The surface soil at the depth between 0-15 cm was loam texture, which contained 50.8 % sand, 40.4 % silt and 8.8 % clay (Table 3.1). The slope of the land was approximately one percent from east to west. There were small undulations which caused uneven water depths at some locations. Farmer cultivated rice every two years and raised cattle in between. Uneven distribution of plant residues was easily observed. The rice variety used in this farm was Cocodrie.

b) Farm 2 was a farm located near Lake Charles. The soil at this site was classified as Crowley series (Soil Survey, 1988). Soil surface was approximately 20-25 cm depth containing 23.3 % sand, 54.8 % silt, and 21.9 % clay and silt loam texture. Rice variety grown was Wells. Water from an under ground well was used for irrigation. Crop rotation included cattle between rice cultivation (every two years).

c) Farm 3 was a farm located North of Crowley. Soil at this site was classified as
Figure 3.1 Three selected commercial farms and Rice Research Station, Crowley.
Table 3.1 Soil particle size distribution and textural class of three studied sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Textural Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm 1</td>
<td>50.8</td>
<td>40.4</td>
<td>8.8</td>
<td>Loam</td>
</tr>
<tr>
<td>Farm 2</td>
<td>23.3</td>
<td>54.8</td>
<td>21.9</td>
<td>Silt Loam</td>
</tr>
<tr>
<td>Farm 3</td>
<td>4.9</td>
<td>81.4</td>
<td>13.7</td>
<td>Silt Loam</td>
</tr>
</tbody>
</table>

Table 3.2 Procedures used for soil testing.

<table>
<thead>
<tr>
<th>Soil Properties</th>
<th>Procedures</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic matter</td>
<td>$1N K_2 Cr_2 O_7 +$ Conc. H$_2$SO$_4$, Colorimeter</td>
<td>Nelson and Sommers, 1982</td>
</tr>
<tr>
<td>pH</td>
<td>1:1 (soil weight : DIW volume)</td>
<td>McLean, 1982</td>
</tr>
<tr>
<td>Available P</td>
<td>$0.03M NH_4 F$ and $0.1M HCl$, ICP</td>
<td>Bray and Kurtz, 1945</td>
</tr>
<tr>
<td>Extractable K, Ca, Mg, Na</td>
<td>$1M$. NH$_4$OAc pH 7.0, ICP</td>
<td>Thomas, 1982</td>
</tr>
<tr>
<td>Sulfur</td>
<td>$0.5M NH_4$OAc and $0.25M H$OAc, ICP</td>
<td>Tabatabai, 1982</td>
</tr>
<tr>
<td>Iron, Manganese, Zinc</td>
<td>$0.005M$ DTPA, pH 7.3, ICP</td>
<td>Lindsay and Norvell, 1978</td>
</tr>
<tr>
<td>Particle Size</td>
<td>Pipette method</td>
<td>Soil Survey, 1996</td>
</tr>
</tbody>
</table>
Crowley series (Soil Survey, 1962). The soil surface was approximately 15-20 cm depth, containing 4.9 % sand, 81.4 % silt, and 13.7 % clay. Soil texture is silt loam. Cropping pattern was rice – soybean – rice. Rice variety was Cocodrie. Under ground water was used for irrigation.

At normal and poor growth areas in each farm platinum electrodes were placed at approximately 10 cm depth from soil surface. Changes in soil Eh were monitored during the growing season using platinum electrodes. Twenty platinum electrodes were installed (10 electrodes at positions with low plant growth and high amount of plant residue and 10 electrodes at positions with high plant density or normal growth). The electrodes were connected to a data logger. Redox measurement were recorded every ten minutes and averaged hourly. Plant density around each electrode location was observed every 2 weeks. Soil samples were taken approximately 30 cm from each electrode. Soil pH samples were collected twice at maximum panicle initiation, and flowering stage. Soil pH, organic matter, phosphorus, potassium, sulfur, iron, manganese, and zinc were analyzed. Soil testing procedures used in soil analysis are shown in Table 3.2. The correlation between organic matter and other elements were performed using Microsoft Excel software.

3.3 Results and Discussion

3.3.1 Soil Redox Potential and Plant Growth

Soil redox potential was plotted against time following planting. Soil redox potentials of selected positions in farm 1 are presented in Figure 3.2. At position 6 (electrode no. 11 and 12) and position 10 (electrode no. 19 and 20), the Eh values were lower than at the
other positions. Plant density in these positions was less than 100 plants per 1 square meter (data not shown). During the draining period redox (Eh) data of all electrodes responded similarly. The average soil Eh values in normal growth and poor growth areas are shown in Figure 3.3. Overall average soil redox value was not significantly different between positions of normal and poor growth. However, plants at poor growth areas reached maturity later than at normal rice growth area.

At farm 2, soil redox potentials recorded among the electrodes were not significantly different (Figure 3.4). Overall average soil redox potentials are shown in Figure 3.5. The redox potential after re-flooding at this farm was lower than at farm 1. Even though soil redox potential was low, poor rice growth in this farm was not observed. The differences parameters between the two sites were soil texture and rice varieties. The soil at farm 2 contained more clay (21.9 %) compared with farm 1 (8.8 %) and had a deeper surface soil layer (20-25 cm) than soil at farm 1 (10-15 cm). At farm 1, the rice variety was Cocodrie was but at farm 2 the rice variety was Wells. Plant density at farm 2 was approximately 250 -300 plants per square meter and remained constant throughout growing season. There also were greatest number of tillers at farm 2 compared with farm 1 and farm 3.

Soil redox potential recorded at farm 3 using the Pt electrodes for selected locations are shown in Figure 3.6. The overall average soil redox potential values are shown in Figure 3.7. Initial soil redox potential consisted of positive values (+ 350 mV) and decreased to approximately 0 mV and then increased following draining. After re-flooding, soil redox potential dropped to below 0 mV.
Figure 3.2 Soil redox potential (Eh) of selected positions in farm 1, position 1 (site 1) and position 3 (site 3) are the area that rice grows well, position 6 (site 6) and position 10 (site 10) are the area that rice was poorly grown (in 2002).
Figure 3.3 Average soil redox potential (mV) in normal growth positions (n=12), and in poor growth positions (n=8) in farm 1 (in 2002).
Redox value at this farm was higher than that measured at farm 2. The adverse effect of organic matter on plant growth (number of tillers) was not observed in this farm. Plant density at this farm was approximately 250 plants per one square meter with low amount of secondary tiller. Most of the stems developed from single seed.

Soil Eh data of farm 3 (Figure 3.6 and 3.7) showed redox response when water was removal from the field. The platinum electrodes were placed in the field when the rice soil had been drained and rice plants were approximately 2-3 weeks old. The redox potential increased when the field was drained during mid season. The drainage practice of this farm consisted of two drainage periods. These two drainages resulted in increasing soil oxidation (as reflected in increased redox potential), which might have reduced toxicity resulting from the decomposition processes of organic matter.

3.3.2 Soil Analyses
Soils samples were collected from the three field sites at two different times. Initial sampling was collected during tillering stage, and the second sampling was collected during flowering stage. The results from soil analyses at farm 1 at tillering, and flowering stage are shown in Table 3.3, and 3.4 respectively. Most of the measured soil parameter values changed little between the first and the second sampling. The average soil pH at farm 1 was 6.12 at tillering and 6.03 at flowering. Soil organic matter was 2.13 and 2.18 % at tillering and flowering, respectively. There was some variation in potassium, iron and soil redox potential.

Soil analyses at tillering and flowering stage for farm 2 are shown in Table 3.5, and Table 3.6, respectively. Soil redox potential, iron, sulfur and potassium at the first sampling showed high variability. There was less variability in soil pH, organic matter,
Figure 3.4 Soil redox potential (mV) at different times from position 1, 2, 3, and 4 in farm 2 (in 2002).
Figure 3.5 Average soil redox potential (mV) at different times from 10 positions of farm 2 (in 2002).
Figure 3.6 Soil redox potential (mV) at different times of selected positions from farm 3 (in 2002).
Figure 3.7 Average soil redox potential (mV) at different times from 10 selected positions of farm 3 (in 2002).
Table 3.3 Soil analysis results from farm 1 at tillering stage.

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SD: 0.10  0.54  5.11  9.32  1.99  23  2.78  0.10  49.7
Table 3.4 Soil analysis results from farm 1 at flowering stage.

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Minimum       | 5.66| 0.83    | 8.86   | 15.11  | 4.74   | 52     | 4.14   | 0.27   | -186.7  |
Maximum        | 6.28| 4.20    | 14.95  | 55.65  | 16.67  | 162    | 15.01  | 0.96   | 79.4    |
Average        | 6.03| 2.18    | 10.41  | 34.63  | 9.34   | 97     | 7.76   | 0.55   | -109.6  |
SD             | 0.15| 0.84    | 1.32   | 11.32  | 2.85   | 30     | 2.87   | 0.19   | 86.6    |
Table 3.5 Soil analysis results from farm 2 at tillering stage.

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Table 3.6 Soil analysis results from farm 2 at flowering stage.

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zinc and manganese. Soil sampling at flowering stage showed a similar pattern with the first sampling. Average soil pH at farm 2 was 5.82 at tillering and 5.80 at maturity stage, which had the lowest soil pH among the three farms. Soil organic matter at this farm was the highest.

Soil analysis data for farm 3 at tillering and flowering stage are show in Table 3.7, and 3.8, respectively. Soil pH at farm 3 was 6.93 and 7.36 at tillering and flowering stages, respectively and was highest among the three farms. Soil organic matter was 1.77 % at tillering and 1.66 % at flowering stage and was the lowest among the three farms. Soil phosphorus at farm 3 was highest among the three farms, 125 and 116 ppm at tillering and flowering stages, respectively. Other measured soil parameters were similar to the first two farms.

3.3.3 Correlations among Soil Chemical Properties

Correlation analysis of soil chemical properties for the three farms was compared within each farm and time of sampling. Correlation analysis (R²) at farm 1, farm 2, and farm 3 at tillering stage are shown in Table 3.9. R² values at farm 1 and farm 2 for some parameters, such as organic matter content, phosphorus, potassium, sulfur, iron, and manganese showed high correlation. However, at the farm 3, R values showed lower correlation among the soil variables as compared to farm 1 and 2. Organic matter and sulfur at farm 3 showed less influence on flooded soil properties as compared to the other two farms.

Correlation values (R²) at flowering stage for farm 1, farm 2, and farm 3 are shown in Table 3.10. R² at farm 1 was the same at flowering stage as at the tillering stage. R² for soil parameters at farm 2 and farm 3 showed significant correlation for
Table 3.7 Soil analysis results from farm 3 at tillering stage.

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Table 3.8 Soil analysis results from farm 3 at flowering stage.

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<td>88.15</td>
<td>45.77</td>
<td>9.79</td>
<td>144</td>
<td>29.39</td>
<td>0.47</td>
<td>-188.1</td>
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<td>14</td>
<td>7.27</td>
<td>1.80</td>
<td>100.36</td>
<td>47.62</td>
<td>12.23</td>
<td>157</td>
<td>22.93</td>
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<td>-248.0</td>
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<td>15</td>
<td>6.91</td>
<td>1.88</td>
<td>82.51</td>
<td>54.64</td>
<td>10.42</td>
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<td>37.98</td>
<td>0.54</td>
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<td>11.51</td>
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<td>1.77</td>
<td>89.31</td>
<td>41.24</td>
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<td>19.56</td>
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<td>1.89</td>
<td>106.29</td>
<td>47.30</td>
<td>10.52</td>
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<td>20.00</td>
<td>0.46</td>
<td>-248.1</td>
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<td>1.29</td>
<td>87.11</td>
<td>51.11</td>
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<td>97.06</td>
<td>49.94</td>
<td>13.14</td>
<td>148</td>
<td>22.70</td>
<td>0.44</td>
<td>-254.5</td>
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Minimum: O.M (%) = 6.91, P = 70.95, K = 37.07, S = 8.62, Fe = 111, Mn = 19.48, Zn = 0.37, Eh = -255.4
Maximum: O.M (%) = 7.70, P = 116.07, K = 54.64, S = 13.14, Fe = 191, Mn = 37.98, Zn = 0.66, Eh = -81.1
Average: O.M (%) = 7.35, P = 92.02, K = 44.83, S = 10.85, Fe = 140, Mn = 24.89, Zn = 0.46, Eh = -200.0
SD: O.M (%) = 0.19, P = 0.20, K = 11.09, S = 4.29, Fe = 21, Mn = 5.07, Zn = 0.07, Eh = 54.1
Table 3.9 Correlations among various soil parameters at tillering stage in a) farm 1, b) farm 2, and c) farm 3.

### a) Farm 1

<table>
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<tr>
<th></th>
<th>pH</th>
<th>O.M (%)</th>
<th>P (ppm)</th>
<th>K (ppm)</th>
<th>S (ppm)</th>
<th>Fe (ppm)</th>
<th>Mn (ppm)</th>
<th>Zn (ppm)</th>
<th>Eh (mv)</th>
</tr>
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<tr>
<td>O.M (%)</td>
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<td>P (ppm)</td>
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<td>0.621**</td>
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<tr>
<td>K (ppm)</td>
<td>0.001</td>
<td>0.754**</td>
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<td>S (ppm)</td>
<td>0.063</td>
<td>0.756**</td>
<td>0.515*</td>
<td>0.813**</td>
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<tr>
<td>Fe (ppm)</td>
<td>0.017</td>
<td>0.690**</td>
<td>0.810**</td>
<td>0.789*</td>
<td>0.710**</td>
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<tr>
<td>Mn (ppm)</td>
<td>0.001</td>
<td>0.663**</td>
<td>0.760**</td>
<td>0.751**</td>
<td>0.583**</td>
<td>0.854**</td>
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<tr>
<td>Zn (ppm)</td>
<td>0.006</td>
<td>0.770**</td>
<td>0.737**</td>
<td>0.791**</td>
<td>0.781**</td>
<td>0.826**</td>
<td>1.000</td>
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<tr>
<td>Eh (mv)</td>
<td>0.111</td>
<td>0.082</td>
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* significant at 5% level
** significant at 1% level

### b) Farm 2

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<th>O.M (%)</th>
<th>P (ppm)</th>
<th>K (ppm)</th>
<th>S (ppm)</th>
<th>Fe (ppm)</th>
<th>Mn (ppm)</th>
<th>Zn (ppm)</th>
<th>Eh (mv)</th>
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<td>O.M (%)</td>
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<td>P (ppm)</td>
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<td>0.786**</td>
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<td>K (ppm)</td>
<td>0.087</td>
<td>0.781**</td>
<td>0.695**</td>
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<tr>
<td>S (ppm)</td>
<td>0.018</td>
<td>0.631**</td>
<td>0.748**</td>
<td>0.713**</td>
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<td></td>
<td></td>
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<tr>
<td>Fe (ppm)</td>
<td>0.013</td>
<td>0.497*</td>
<td>0.302</td>
<td>0.401</td>
<td>0.199</td>
<td>1.000</td>
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<tr>
<td>Mn (ppm)</td>
<td>0.046</td>
<td>0.624**</td>
<td>0.560*</td>
<td>0.533*</td>
<td>0.331</td>
<td>0.754**</td>
<td>1.000</td>
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</tr>
<tr>
<td>Zn (ppm)</td>
<td>0.059</td>
<td>0.778**</td>
<td>0.832**</td>
<td>0.819**</td>
<td>0.886**</td>
<td>0.325</td>
<td>0.493*</td>
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<tr>
<td>Eh (mv)</td>
<td>0.128</td>
<td>0.047</td>
<td>0.004</td>
<td>0.027</td>
<td>0.034</td>
<td>0.000</td>
<td>0.001</td>
<td>0.038</td>
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* significant at 5% level
** significant at 1% level

### c) Farm 3

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<th>K (ppm)</th>
<th>S (ppm)</th>
<th>Fe (ppm)</th>
<th>Mn (ppm)</th>
<th>Zn (ppm)</th>
<th>Eh (mv)</th>
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<tr>
<td>O.M (%)</td>
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<td>1.000</td>
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</tr>
<tr>
<td>P (ppm)</td>
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<td>0.240</td>
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</tr>
<tr>
<td>K (ppm)</td>
<td>0.027</td>
<td>0.535*</td>
<td>0.578**</td>
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<td>S (ppm)</td>
<td>0.098</td>
<td>0.439</td>
<td>0.582**</td>
<td>0.572*</td>
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<tr>
<td>Fe (ppm)</td>
<td>0.009</td>
<td>0.338</td>
<td>0.604**</td>
<td>0.552*</td>
<td>0.308</td>
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<tr>
<td>Mn (ppm)</td>
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<td>0.172</td>
<td>0.002</td>
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<td>0.016</td>
<td>0.228</td>
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<tr>
<td>Zn (ppm)</td>
<td>0.008</td>
<td>0.539*</td>
<td>0.355</td>
<td>0.484*</td>
<td>0.351</td>
<td>0.530*</td>
<td>0.107</td>
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<tr>
<td>Eh (mv)</td>
<td>0.093</td>
<td>0.073</td>
<td>0.139</td>
<td>0.213</td>
<td>0.304</td>
<td>0.105</td>
<td>0.001</td>
<td>0.147</td>
<td>1.000</td>
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</tbody>
</table>

* significant at 5% level
** significant at 1% level
only a number of parameters. Soil organic matter in farm 3 was correlated with zinc. Phosphorus, potassium, sulfur, and iron were not correlated with any measured soil parameters.

3.3.4 Regression Analysis

Since the results from correlation analysis indicated that there was significant R square between organic matter and selected parameters. Regressions analysis was performed to emphasize the effect of organic matter on various soil properties.

3.3.4.1 Tillering Stage

Regression analyses for site 1 at tillering stage are shown in Figure 3.8 a, b, and c. All regression data showed that increasing organic matter resulted in increase soil plant nutrient levels. For example, in Figure 3.8 a, the regression equation for phosphorus was: \[ y = 14.916x + 5.501 \], where \( x \) = organic matter (%). The regression from Figure 3.8 a, b and c showed that phosphorus, potassium, iron, sulfur, manganese, and zinc were positively related with soil organic matter.

Regression analysis conducted at tillering stage at farm 2 are shown in Figure 3.9 a, b, and c. The regression analysis showed the same trend that was observed at farm 1.

At farm 3, the regression equations of phosphorus, potassium, and zinc in soil were positively related to amount of soil organic matter (Figure 3.10 a, and 3.10 b).

3.3.4.2 Flowering Stage

Regression analyses among the different soil parameters at flowering stage of site 1 are shown in Figure 3.11 a, b, and c. The regressions conducted at this sampling period at farm 1 were similar as the tillering stage. At farm 2, significantly correlation of soil organic matter was found for only sulfur, potassium, and zinc in soil (Figure 3.12 a, b).
Table 3.10 Correlations among various soil parameters at flowering stage in a) farm 1, b) farm 2, and c) farm 3.

### a) Farm 1

<table>
<thead>
<tr>
<th></th>
<th>pH</th>
<th>O.M (%)</th>
<th>P (ppm)</th>
<th>K (ppm)</th>
<th>S (ppm)</th>
<th>Fe (ppm)</th>
<th>Mn (ppm)</th>
<th>Zn (ppm)</th>
<th>Eh (mv)</th>
</tr>
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<td>O.M (%)</td>
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<td>P (ppm)</td>
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<tr>
<td>K (ppm)</td>
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<td>0.767**</td>
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<tr>
<td>S (ppm)</td>
<td>0.408</td>
<td>0.915**</td>
<td>0.477*</td>
<td>0.718**</td>
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</tr>
<tr>
<td>Fe (ppm)</td>
<td>0.409</td>
<td>0.806**</td>
<td>0.500*</td>
<td>0.714**</td>
<td>0.749**</td>
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<td>Mn (ppm)</td>
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<td>0.722**</td>
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<td>Zn (ppm)</td>
<td>0.424</td>
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<td>0.672**</td>
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<td>0.495*</td>
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<td>Eh (mv)</td>
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<td>0.036</td>
<td>0.032</td>
<td>0.107</td>
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* significant at 5% level
** significant at 1% level

### b) Farm 2

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<th>O.M (%)</th>
<th>P (ppm)</th>
<th>K (ppm)</th>
<th>S (ppm)</th>
<th>Fe (ppm)</th>
<th>Mn (ppm)</th>
<th>Zn (ppm)</th>
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<td>Mn (ppm)</td>
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* significant at 5% level
** significant at 1% level

### c) Farm 3

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<th>Fe (ppm)</th>
<th>Mn (ppm)</th>
<th>Zn (ppm)</th>
<th>Eh (mv)</th>
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<td>K (ppm)</td>
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<tr>
<td>Zn (ppm)</td>
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<td>0.812**</td>
<td>0.448*</td>
<td>0.616**</td>
<td>0.601**</td>
<td>0.421</td>
<td>0.044</td>
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<td>0.017</td>
<td>0.040</td>
<td>0.015</td>
<td>0.003</td>
<td>0.041</td>
<td>0.001</td>
<td>0.087</td>
<td>0.021</td>
<td>1.000</td>
</tr>
</tbody>
</table>

* significant at 5% level
** significant at 1% level
These results suggested that following flooding at farm 2, there were no relationship to the amount of available nutrient in soil to the amount of soil organic matter present. Only zinc was significantly correlated to soil organic matter in farm 3 (Figure 3.13). This finding may be attributed to the low amount of organic matter in this farm.

3.4 CONCLUSIONS AND SUGGESTIONS

The results from these studies indicated that measured soil redox potential for the three farms may be used as indicator for predicting rice growth. Soil redox potential can be used as indicator to predict soil oxygen demand and other chemical species. Low soil redox potential alone, however, cannot be used to predict plant growth. From this experiment, the overall average redox potential at farm 2 was lower than farm 1 but there were no measured adverse affects on plant growth at farm 2, compared with farm 1 where reduction in plant growth and development were observed.

Overall soil redox potential value in farm 2 was lower than farm 1 but plant growth in farm 2 was not affected by the lower redox potential. Soil properties and rice variety grown at farm 2 were differed from farm 1. The higher clay fractions in soil at farm 2 (21.9 %) compared with farm 1 (8.8 %), might have created a greater potential to retain organic matter and plant residue. In contrast soil at farm 1 contained more sand (50.8 %) while sand content at farm 2 was 23.3%. The greater porosity may have limited the ability of this soil to retain organic matter. Flooded water entering the field at farm 1 containing floated organic matter debris which tended to accumulation on the soil surface. The organic matter accumulation on the surface may have restricted rice growth.

Flooded rice soils are very complex system and different among farm sites. Soil
Figure 3.8 Regression analyses between O.M. and selected parameters in farm 1 at tillering stage.
a) O.M. vs P<sup>(□)</sup> & K<sup>(△)</sup>

b) O.M. vs Fe<sup>(□)</sup> & S<sup>(△)</sup>

c) O.M. vs Mn<sup>(□)</sup>& Zn<sup>(△)</sup>

Figure 3.9 Regression analyses between O.M. and selected parameters in farm 2 at tillering stage.
Figure 3.10 Regression analyses between O.M. and selected parameters in farm 3 at tillering stage.
a) O.M. vs P (□) & K (△)

![Graph a)

b) O.M. vs Fe (□) & S (△)

![Graph b)

c) O.M. vs Mn (□) and Zn (△)

![Graph c)

Figure 3.11 Regression analyses between O.M. and selected parameters in farm 1 at flowering stage.
Figure 3.12 Regression analyses between O.M. and selected parameters in farm 2 at flowering stage.
Figure 3.13  Regression analyses between O.M. and zinc (Zn) in farm 3 at flowering stage.
chemical and physical properties can play a significant role in rice production.

Soil texture at farm 2, which contained more clay content, can reduce toxicity associated with organic matter compared with soil from farm 1, which contained less clay (Table 3.1). The high absorption capacity of clay tends to reduce the amount of toxic compound in soil solution.

The major findings from this experiment are listed below:

1) Redox potential was inversely related to soil organic matter content (farm 1), i.e. low soil redox potential was measure in farm 1, and farm 2 with high organic matter content.

2) Redox potential can be used as a parameter to predict plant growth under some environmental conditions.

3) Water management techniques may serve as a method to reduce toxicity from organic matter. The evidence from farm 3 showed that increasing number of drainage period during the growing season resulted in better rice growth.

4) Soil texture might play a significant role to alleviate toxicants in flooded soil.

   High clay content of soil from farm 2 apparently reduced toxicity to the rice plant resulting from high soil organic matter. Clay may absorb some toxic organic chemicals that are released from organic matter during decomposition processes.

   Future research should focus on the effect of organic matter (source and rate) on growth of several rice varieties, and draining effects on plant growth. The experimental design should be designed to evaluate the impact of different source and rates of organic matter application on rice growth and yield.
4.1 INTRODUCTION

Flooding plays a very significant role in wetland plant growth and development. Lowland rice soils undergo a unique sequence of chemical and microbial transformations related to the changes in soil water content that occur during a cropping cycle. Flooding causes several chemical changes in anaerobic conditions such as, reduction of soil redox potential, reduction of \( \text{NO}_3^- \), \( \text{SO}_4^{2-} \), \( \text{Mn}^{4+} \), \( \text{Fe}^{3+} \) and generation of \( \text{CO}_2 \), \( \text{CH}_4 \), and \( \text{H}_2\text{S} \) (Ponnampерuma, 1972; De Datta, 1981). Soil reduction processes can increase the availability of nutrients such as P, K, Si, and Mo, but may decrease the availability of Zn, S, and Cu (Dobermann and Fairhurst, 2000).

Rice straw is the major organic material source in rice fields. Incorporation of rice straw and remaining stubble into the soil returns most of the nutrients and helps to maintain rice grain yield over the long-term period. Straw incorporation has been reported to improve soil condition and plant growth. For example, Yoneyama and Yoshida (1977) concluded that straw incorporation enhanced immobilization and mineralization of nitrogen.

The role of soil organic matter as a source of nutrients, especially N, P and S, through mineralization has long been documented (Jarvis et al., 1996 and Zhu et al., 1984). Powlson and Olk (2000) claimed that nutrient supplied through soil organic matter mineralization can lead to a decreased for inorganic fertilizers. The slow release of
nutrients from old fractions of soil organic matter and the more rapid release from freshly
crop residues are both of importance.

Although the principles of nutrient accumulation in soil organic matter and its
release have been well known, accurately predicting available quantity for crop growth in
a specific condition has proved to be difficult (Powlson and Olk, 2000). Horwath and
van Kessel (1998) monitored large-scale plots of varying rice straw residue treatments.
They concluded that straw incorporation without fertilizer N addition increased grain
yield. Suggesting straw served as a source of N for rice growth. Eagle et al. (2000) also
reported that straw retention in rice soils resulted in increasing soil N supply as evidenced
by greater plant N uptake. The increase in soil nitrogen availability is associated with
both direct and an indirect effect of oxygen deficiency in the root environment, which
relates to organic matter decompositions. Excess soil organic matter levels can have
negative effects on plant growth resulting in mineral deficiencies and/or toxicities by high
Fe and sulfide, found in the reduced soil environment (Dobermann and Fairhurst, 2000).
In cool climates and in poorly drained fields, incorporation of rice straws have also been
shown to reduce rice yields (Tanaka, 1978).

Gaseous products in submerged soils are associated to organic materials
decomposition (Neue and Scharpenseel, 1984). Upon flooding, soil microorganisms
rapidly consume any O₂ in the soil within a few hours of soil submergence
(Ponnamperuma, 1972). The end products of gas are CO₂, H₂, CH₄, NH₃ and H₂S related
to the anaerobic decomposition of organic matter (Ponnamperuma, 1972). Soil
environments factors such as soil type, availability of nutrients, pH and Eh vary in
decomposition patterns and also in the gaseous products (Neue and Scharpenseel, 1984).
The gases products as result of high organic matter decompositions in submerged soils significantly influence plant growth. A number of recent researches have shown that flooded soil containing high organic matter enhanced more methane emission as compared to soil containing less organic matter.

Methane concentration in the atmosphere has more than double during the last 200 years (IRRI, 2002). The emission of methane from rice fields to atmosphere has long been known, but comprehensive study of methane fluxes from rice fields have been reported only since the early 1980s (Neue, 1993). Water regime, temperature and soil properties, as well as rice variety are the major factors determining the production and flux of methane in rice fields (IRRI, 2002). According to Wassmann et al. (2002) organic inputs into the soil are generally enhanced methane emissions. Methane production in anaerobic soils is derived mainly from decomposing soil organic matters such as plant debris, and applied organic fertilizers (Neue 1993). Methane production in rice soils generally increases during the cropping season (Schutz et al., 1989). The fluctuations of the soil temperature and the rice plant-growing activities importantly contribute to the diurnal fluctuations in methane emission (Wang et al., 1993). Rennenberg et al. (1992) noted that both quantity and quality of the available carbon source either from amended organic matter or root exudates significantly influences the methane production. The seasonal variations are explained by the change in available substrate and other factors in the rice fields (Minami and Neue, 1994).

Water management is a key factor in mitigating methane emission from rice fields. Increasing rate of water percolation in rice soil would be and important strategy for allowing oxygen to enter the reduced soil and decrease methane production (Neue,
1993). This technique required more water and may cause nutrients loss through leaching (Neue, 1993). Reducing the amount of water-use for wetland rice production is still controversial since there are critical issues associated with yield loss. De Datta (1981) noted that water stress at any growth stage reduces rice yield. Soil moisture content of -50 kPa (slightly above field capacity) may reduce rice grain yield by 20-25% as compared to continually flooded treatments. Rice is most sensitive to water stress during the reproductive stage. Water shortage at this growth stage can cause yield loss by lowering sterility (Yoshida, 1981). Water deficit during the vegetative stage can reduce plant height, tiller number, and leaf area, and grain yields if plants do not have adequate time to recover before flowering (Castillo et al. 1992).

The duration of moisture stress is more important than the plant growth stage at which the stress occurs. Intermittent drying or keeping soils saturated during the growing season either vegetative or reproductive phase lowers rice yields significantly in most tropical rice fields (Borell et al., 1991). However, in some parts of China, Japan, and Korea, intermittent wetting and drying cycle during rice growing season governs with rice yields, because organic and inorganic toxins accumulated from the decomposition under low soil temperature at early growing season is diminished. Short aeration periods at the end of the tillering stage can improve rice yields if followed by flooding (Wang Zhaoqian, 1986 (cited in Neue, 1993)).

The objectives of this research were i) to monitor soil pH and Eh change as affected by flooding conditions and soil organic matter content, ii) to quantify nutrient availability and uptake under different flooding condition, iii) to determine methane and nitrous oxide emission as affected soil organic matter and flooding regime, and iv) to
investigate whether draining water for some periods of time during the growing season can alleviate reduced rice growth associated with high soil organic matter content.

4.2 MATERIALS AND METHODS

A Crowley silt loam (Typic Albaqualf) collected from the Louisiana Rice Research Station at Crowley, LA was used in this study. The soil contained 0.84 % total C, 0.38 % total N and pH of 6.9 (1:1 soil: water). Soil sample at 0-20 cm depth was air-dried, crushed and thoroughly mixed.

Ten kilogram of soil sample was transferred to 3.5-gallon plastic pots. Rice straw (ground pass 0.5 mm screen) was mixed with soil in the pots at rates of 0, 4, 8, and 16 t ha$^{-1}$. A 2 x 2 x 4 factorial experiment was arranged in a split split-plot design with two water management practices as main plot treatments (alternately flooded and drained, and continuously flooded), two rates of potassium (0, and 80 kg ha$^{-1}$) as subplot treatment, and four rates of rice straw incorporation as sub-subplot treatment (0, 4, 8, and 16 t ha$^{-1}$), with four replications. The experiment was conducted at the LSU campus greenhouse, Baton Rouge. Platinum electrodes were placed in the pots at a 10 cm depth. Redox data were recorded hourly from plot establishment until harvesting via data loggers. Pregenerated seeds of variety Cocodrie were planted at the rate of 9 plants per pot. Nitrogen fertilizer (3% $^{15}$N labeled NH$_4$Cl) was split applied at rate of 75 kg N ha$^{-1}$ at three and six weeks after planting. Phosphorus was incorporated in all pots before planting at the rate of 60 kg P ha$^{-1}$. Potassium was applied at 0 and 80 kg ha$^{-1}$ before planting according to the treatments.

4.2.1 Rice Growth Measurement
Seedling survival was measured at one week after planting. Any missing or dead seedling was replanted two weeks after planting with extra seedlings. Plant samples were collected from two rice-hills at the tillering, panicle initiation, flowering, and maturity stages. Tiller number, plant height, and weigh (after drying with oven at 65-70 °C for 72 hours) were determined. At maturity stage, number of panicles, panicle dry weight, root dry weight, filled grain weight and unfilled grain weight were also recorded.

4.2.2  $^{15}$N and Nutrient Uptake Measurement

Plant samples were ground and passed through a 0.05 mm screen. Samples were weighed (approximately 15-18 milligram, except 6-7 mg for grain samples) and then packed it into 5 x 9 mm tin capsules. $^{15}$N atom % and total N was analyzed by Isotope Ratio Mass Spectrometers, Europa Integra (Stable Isotope Laboratory, UC Davis). Nitrogen derived from fertilizer (% ndff), nitrogen derived from soil (% ndfs), nitrogen use efficiency (%), and total nitrogen uptake were obtained from the results of $^{15}$N and total N in plant samples. Total nutrient content and plant elemental uptake of P, K, Ca, Mg, S, Zn, Fe and Mn were analyzed only at panicle initiation stage. Plant elemental uptake was calculated using the result of chemical analysis multiplied by the dry matter weight of the samples from each pot.

4.2.3  Soil Sampling and Analysis

Soil samples were collected from all pots at harvest by pushing a clear plastic tube (5 cm diameter) into the soil until reaching the bottom of the pots. Soil samples were air-dried and analyzed for pH, organic matter, available P, extractable K, Ca, Mg, Na, and Fe using the procedures that are shown in Table 3.2.
4.2.4 Methane and Nitrous Oxide Flux Measurement

Methane and nitrous oxide emission from the treatments were measured using diffusion chambers (Lindau et al., 1991) places over the soil plant system. The sketch of the closed chamber system is presented in Figure 4.1. The base units were constructed of clear Plexiglas (30 x 30 x 30 cm). The removable diffusion chambers (top phase) were also constructed of the same dimension of Plexiglas which containing a 9-volt fan mounted on the inside, which was used to mix the air column within the chamber prior to sampling. During flux measurements the trough was filled with water in order to seal the diffusion chambers, which were placed on the bases. Pressure inside the chamber was relieved through the use of a coiled 1.5-meter Tygon tubing apparatus. This theoretically maintained pressure equilibrium between the outside and the inside of the chamber while minimizing any introduction of exterior gases. A rubber septum serving as a sampling port and a thermometer were also located on the top of each chamber. Additional base units were stacked as the rice grew in order to insure the chamber fit over the rice plants.

A 15 ml sample was withdrawn from the top chambers using a 20 ml gas-tight syringe at 0 and 15 minute for methane, and 0, 2 hours for nitrous oxide. The gas samples were injected into a silicone sealed Vacutainer. These Vacutainers were evacuated using a high-vacuum preparation line to remove residual gases (Lindau et al., 1991). Once evacuated, the tubes were sealed with silicone rubber and subsequently resealed after injecting of the sample. Floodwater heights and air temperatures inside the chamber were recorded for calculation headspace volume and emission rate.

Gas samples were analyzed for methane and nitrous oxide using a Shimadzu GC14-A flame ionization gas chromatograph. A gas-tight syringe was used to inject
Figure 4.1 Diagram of closed diffusion chambers system (Lindau et al., 1991) used to collect methane and nitrous oxide emission from both pot and field experiments.
a 1.0 ml (methane), and 2.0 ml (nitrous oxide) gas sample into a stainless steel column. The detector temperatures were set at 200 and 270 °C (for CH₄ and N₂O). Integration and analysis were accomplished with the use of Shimadzu R-14AC Chromatopac. Raw data was recorded and used to calculate the flux of CH₄ and N₂O per unit area. A closed chamber equation (Rolston, 1986) was used to estimate methane and nitrous oxide fluxes from each treatment.

\[
F = \left(\frac{V}{A}\right) \left(\frac{(T+C)}{T}\right) \left(\frac{\Delta c}{\Delta t}\right)
\]

Where:  
- \( F \) = flux of methane and nitrous oxide from soil/water surface  
- \( V \) = headspace volume of chamber (L)  
- \( A \) = surface area (base-soil surface area)  
- \( T \) = absolute temperature  
- \( C \) = temperature (Celsius)  
- \( \frac{\Delta c}{\Delta t} \) = change in gas concentration per unit time

4.2.5 Statistical Analysis

Analysis of variance (ANOVA) was used to measure the significance among treatments and then mean comparison was calculated by Duncan’s Multiple Range Test (DMRT). Statistical analyses were performed using IRRISTAT Software (IRRI, 1992).

4.3 RESULTS AND DISCUSSION

4.3.1 Soil pH and Redox Potential (Eh)

Soil pHs were similar in both water management treatments. Soil pH of alternately flooded and drained treatment ranged between 6.3 and 7.4 during the first two weeks with less fluctuation in pH after this period. The highest pH values were found in treatments with lower soil plant residue. Lower soil pH values were measured in the
treatments with the higher rates of plant residue application. Plant residue strongly influences soil pH until the third week after planting in the continuously flooded. The lower soil pH from plant residue lasted longer in the alternately flooded and drained treatment. No effect of potassium on soil pH was found in both water management treatments (Fig 4.2, and 4.3).

Soil redox potential (Eh) in alternately flooded and drained and continuously flooded (Fig 4.4) was highly correlated to plant residue application. The higher plant residue treatments resulted in lower soil redox potential. During mid season, soil redox potential was slightly increased in both water management treatments. This was likely due to rice roots releasing oxygen to soil solution. The water management treatments and potassium addition had no significant effect on soil redox potential.

4.3.2 Plant Growth

Seedling development one week after planting was significantly (p <0.01) different between the two water management treatments (Table 4.1). Higher rates of plant residue (8 and 16 t ha\(^{-1}\)) decreased seedling number significantly in both potassium application rates in the continuously flooded treatment (6.8, and 3.5 for K 0 and 7.0 and 3.3 plant pot\(^{-1}\) for K 80). The data, however, was not significantly different between rates of potassium. Plant number in alternately flooded and drained treatment was not significantly different among potassium and plant residue application rates.

At tillering stage, rice grown in high plant residue treatment (16 t ha\(^{-1}\)) in the alternately flooded and drained treatment produced more stems than the low plant residue treatments. In the continuously flooded treatment, the highest plant residue application rates (16 t ha\(^{-1}\)) in the treatment without added potassium had the lowest plant number per
Figure 4.2 Effect of rice straw on soil pH of the alternately flooded and drained (F/D), a) without potassium, b) 80 kg K ha\(^{-1}\). 0, 4, 8, and 16 = rice straw incorporation rates (t ha\(^{-1}\)).
Figure 4.3 Effect of rice straw on soil pH of the continuously flooded (F), without potassium, b) 80 kg K ha\(^{-1}\). 0, 4, 8, and 16 = rice straw incorporation rates (t ha\(^{-1}\)).
Figure 4.4 Effect of rice straw application on soil redox potential, a) alternately flooded and drained (F/D), b) continuously flooded (F). 0, 4, 8, and 16 = rice straw incorporation rates (t ha$^{-1}$).
Table 4.1 Effect of rice straw, potassium, and water management treatments on plant number (per pot) at different growth stages of rice

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha⁻¹)</th>
<th>1st week</th>
<th>Tillering</th>
<th>Panicle initiation</th>
<th>Flowering</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
</tr>
<tr>
<td>Alt. Flooded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>and Drained</td>
<td>0</td>
<td>9.0 a</td>
<td>9.0 a</td>
<td>12.0 ab</td>
<td>8.8 b</td>
<td>7.0 b</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>9.0 a</td>
<td>8.8 a</td>
<td>9.8 bc</td>
<td>8.8 b</td>
<td>7.3 b</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8.5 a</td>
<td>8.8 a</td>
<td>8.5 c</td>
<td>10.3 b</td>
<td>8.8 ab</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>9.0 a</td>
<td>8.8 a</td>
<td>14.5 a</td>
<td>14.8 a</td>
<td>10.8 a</td>
</tr>
<tr>
<td>Continuously</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flooded</td>
<td>0</td>
<td>8.8 a</td>
<td>8.8 a</td>
<td>10.0 a</td>
<td>6.5 a</td>
<td>10.3 a</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>8.8 a</td>
<td>8.0 a</td>
<td>10.5 a</td>
<td>7.0 a</td>
<td>9.0 a</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>6.8 b</td>
<td>7.0 b</td>
<td>8.8 a</td>
<td>5.5 a</td>
<td>7.0 a</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>3.5 c</td>
<td>3.3 c</td>
<td>5.0 b</td>
<td>7.0 a</td>
<td>9.3 a</td>
</tr>
<tr>
<td>CV (water)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.1</td>
<td>26.1 **</td>
<td>16.5 *</td>
<td>24.3 ns</td>
<td>9.9 **</td>
<td></td>
</tr>
<tr>
<td>CV (K)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.2</td>
<td>22.4 *</td>
<td>30.8 ns</td>
<td>27.5 ns</td>
<td>7.5 ns</td>
<td></td>
</tr>
<tr>
<td>CV (straw)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.7</td>
<td>25 ns</td>
<td>25.5 **</td>
<td>25.8 **</td>
<td>16.1 **</td>
<td></td>
</tr>
</tbody>
</table>

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level.
ns = non significant, * = significant at 5% level, ** = significant at 1% level.
pot (5.0). For potassium application at the rate of 80 kg ha\(^{-1}\) there was no effect on plant number. These results were also observed at the panicle initiation stage. However, at flowering and maturity stages plant numbers in high plant residue application rates was greater than low organic matter addition in both potassium and water management treatments.

At tillering, plant height in the continuously flooded treatment was lower at the high plant residue treatment rate for both potassium treatments. In the alternately flooded and drained treatment, plant height increased slightly with increasing soil plant residue levels but was not significantly different for treatments without potassium (Table 4.2). For the higher plant residue treatment, plant height at panicle initiation, flowering, and maturity stages was greater than plant height for the lower plant residue rates in both potassium levels and water management treatments. In the alternately flooded and drained treatment, the greatest plant height was measured at 8 t ha\(^{-1}\) added plant residue under both potassium application rates.

Plant dry matter weight in the continuously flooded treatment at tillering stage was highest in the treatment without added plant residue. In contrast, plant dry matter weight was increased when increasing levels of plant residue in the alternately flooded and drained treatment (Table 4.3). The average plant dry weight for non potassium treatments was slightly lower compared with the potassium application treatments (80 kg ha\(^{-1}\)) but was not significantly different. At panicle initiation stage, dry matter weight distribution was similar to the tillering stage. Increasing plant residue application rates also resulted in significant increase in dry matter weight at flowering and maturity stages. The effect of potassium on plant dry matter weight was not significantly different at both
Table 4.2 Effect of rice straw, potassium, and water management treatments on plant height (cm).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha⁻¹)</th>
<th>Tillering</th>
<th>Panicle initiation</th>
<th>Flowering</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
</tr>
<tr>
<td>Alt. Flooded and Drained</td>
<td>0</td>
<td>51 a</td>
<td>52 a</td>
<td>63 b</td>
<td>65 c</td>
</tr>
<tr>
<td>4</td>
<td>52 a</td>
<td>50 ab</td>
<td>63 b</td>
<td>69 bc</td>
<td>88 ab</td>
</tr>
<tr>
<td>8</td>
<td>53 a</td>
<td>44 b</td>
<td>73 a</td>
<td>75 a</td>
<td>91 a</td>
</tr>
<tr>
<td>16</td>
<td>54 a</td>
<td>52 a</td>
<td>71 a</td>
<td>72 ab</td>
<td>90 ab</td>
</tr>
<tr>
<td>Con. Flooded</td>
<td>0</td>
<td>55 a b</td>
<td>53 a</td>
<td>67 b</td>
<td>67 b</td>
</tr>
<tr>
<td>4</td>
<td>56 a</td>
<td>51 ab</td>
<td>66 b</td>
<td>68 b</td>
<td>86 b</td>
</tr>
<tr>
<td>8</td>
<td>47 c</td>
<td>45 b</td>
<td>73 a</td>
<td>71 b</td>
<td>93 a</td>
</tr>
<tr>
<td>16</td>
<td>48 bc</td>
<td>48 ab</td>
<td>75 a</td>
<td>79 a</td>
<td>92 a</td>
</tr>
<tr>
<td>CV (water)</td>
<td>8.9 ns</td>
<td>3.9 **</td>
<td>3.9 ns</td>
<td>1.9 ns</td>
<td></td>
</tr>
<tr>
<td>CV (K)</td>
<td>12.5 ns</td>
<td>7.2 ns</td>
<td>6.6 ns</td>
<td>5.3 ns</td>
<td></td>
</tr>
<tr>
<td>CV (straw)</td>
<td>9.3 *</td>
<td>5.4 **</td>
<td>3.4 **</td>
<td>2.8 **</td>
<td></td>
</tr>
</tbody>
</table>

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level.

ns = non significant, * = significant at 5% level, ** = significant at 1% level.
Table 4.3 Effect of rice straw, potassium, and water management treatments on dry matter weight (g pot\(^{-1}\)).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha(^{-1}))</th>
<th>Tillering</th>
<th>Panicle initiation</th>
<th>Flowering</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
</tr>
<tr>
<td>Alt. Flooded and Drained</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.52 ab</td>
<td>1.82 b</td>
<td>6.50 b</td>
<td>7.01 b</td>
<td>24.65 ab</td>
</tr>
<tr>
<td>4</td>
<td>2.12 b</td>
<td>1.65 b</td>
<td>7.02 ab</td>
<td>8.65 b</td>
<td>19.95 b</td>
</tr>
<tr>
<td>8</td>
<td>2.03 b</td>
<td>1.50 b</td>
<td>8.55 ab</td>
<td>8.88 b</td>
<td>19.37 b</td>
</tr>
<tr>
<td>16</td>
<td>3.18 a</td>
<td>2.97 a</td>
<td>9.99 a</td>
<td>11.98 a</td>
<td>32.36 a</td>
</tr>
<tr>
<td>Con. Flooded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.18 a</td>
<td>1.62 a</td>
<td>9.96 a</td>
<td>7.68 a</td>
<td>22.11 b</td>
</tr>
<tr>
<td>4</td>
<td>2.10 a</td>
<td>1.45 ab</td>
<td>6.78 b</td>
<td>7.33 a</td>
<td>19.43 b</td>
</tr>
<tr>
<td>8</td>
<td>1.04 b</td>
<td>0.75 b</td>
<td>5.92 b</td>
<td>6.89 a</td>
<td>21.13 b</td>
</tr>
<tr>
<td>16</td>
<td>0.72 b</td>
<td>0.98 ab</td>
<td>7.27 ab</td>
<td>7.87 a</td>
<td>38.04 a</td>
</tr>
<tr>
<td>CV (water)</td>
<td>11.3 **</td>
<td>31.6 ns</td>
<td>19.6 ns</td>
<td>24.5 **</td>
<td></td>
</tr>
<tr>
<td>CV (K)</td>
<td>38.7 ns</td>
<td>17.7 ns</td>
<td>26.3 ns</td>
<td>24.1 ns</td>
<td></td>
</tr>
<tr>
<td>CV (straw)</td>
<td>30.3 **</td>
<td>25.2 ns</td>
<td>27.9 **</td>
<td>14.4 **</td>
<td></td>
</tr>
</tbody>
</table>

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level.

ns = non significant, * = significant at 5% level, ** = significant at 1% level.
growth stages. The alternately flooded and drained treatments resulted in significantly
greater (p <0.05) dry matter weight compared with the continuously flooded treatment.

Yield component was statistically compared based on panicle numbers, panicle
dry weight, filled grain weight, unfilled grain weight, root dry weight, shoot-root ratio,
and panicle-stem weight ratio. Panicle numbers in the high plant residue treatments was
higher than the numbers for lower plant residue treatments under both water management
treatments (Table 4.4). The alternately flooded and drained treatment resulted in
significantly higher panicle number than the continuously flooded treatment. Potassium
application had no affect on the panicle numbers in either water management treatments.
Panicle dry weight of the continuously flooded treatment was highest in the treatment
which received 16 t ha\(^{-1}\) of plant residue and was significantly different from other
treatments at both potassium application levels (p > 0.05). The alternately flooded and
drained treatment, (at all rates of plant residue addition) had significantly higher panicle
dry weight than the treatment without added plant residue. There was no effect of
potassium on the panicle dry weight. The panicle dry weight of the alternately flooded
and drained treatment was greater than the continuously flooded treatment at all levels of
plant residue. Filled grain weight among the treatment paralleled panicle weight. Root
dry weight of plants grown under the high plant residue treatments was higher than plants
grown in the lower plant residue treatments. Potassium addition and water management
treatments did not affect plant root dry weight. It was, however, difficult to separate the
dead roots from the previous sampling (at flowering stage) from the live root samples.

The panicle/stem ratios decreased with increasing rate of plant residue addition
for both water management treatments (Fig. 4.5). Result showed that plant residue
Table 4.4 Effect of rice straw, potassium, and water management treatments on yield component (number pot⁻¹, and g pot⁻¹)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha⁻¹)</th>
<th>Panicle number</th>
<th>Panicle weight</th>
<th>Filled Grain weight</th>
<th>Unfilled Grain weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
</tr>
<tr>
<td>Alt. Flooded and Drained</td>
<td>0</td>
<td>14.8 c</td>
<td>18.0 b</td>
<td>29.04 b</td>
<td>35.06 b</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>19.5 b</td>
<td>20.8 ab</td>
<td>42.41 a</td>
<td>44.18 a</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>20.0 b</td>
<td>17.8 b</td>
<td>42.21 a</td>
<td>39.61 ab</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>25.8 a</td>
<td>23.3 a</td>
<td>42.25 a</td>
<td>44.23 a</td>
</tr>
<tr>
<td>Con. Flooded</td>
<td>0</td>
<td>13.8 b</td>
<td>16.8 a</td>
<td>21.32 b</td>
<td>34.94 ab</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>17.0 ab</td>
<td>15.0 a</td>
<td>23.43 b</td>
<td>34.69 ab</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>14.0 ab</td>
<td>15.8 a</td>
<td>21.60 b</td>
<td>29.82 b</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>18.3 a</td>
<td>17.0 a</td>
<td>39.23 a</td>
<td>40.33 ab</td>
</tr>
</tbody>
</table>

CV (water) 5.2 ** 10.7 ** 12.1 ** 27.2 ns
CV (K) 11.3 ns 13.3 ** 26.4 ns 31.9 ns
CV (rice straw) 15.8 ** 15.8 ** 17.0 ** 20.8 **

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level.

ns = non significant, * = significant at 5% level, ** = significant at 1% level.
addition increased shoot weight rather than grain weight. Shoot and root ratio was not significantly different between any plant residue treatment rates (Fig 4.6). The ratio of shoot to root in the alternately flooded and drained treatment was greater than that of continuously flooded treatment. Effect of plant residue on unfilled grain weight in the continuously flooded treatment was significantly greater than unfilled grain weight in the alternately flooded and drained treatment (Fig. 4.7).

4.3.3 \(^{15}\)N Uptake

Atom % \(^{15}\)N in plant tissue in all four sampling stages (tillering, panicle initiation, flowering, and maturity stage) in the high plant residue treatment was significantly (p <0.05) lower than that the low plant residue treatment (Table 4.5). Mineralization of the nitrogen in the added organic matter and subsequent plant uptake tended to dilute the \(^{15}\)N fertilizer nitrogen in plant tissue. No effects of potassium or water management treatments on atom % \(^{15}\)N content of plant tissue were observed. The highest atom % \(^{15}\)N level in the plant tissue was detected at panicle initiation stage under both water management treatments. Total nitrogen (%) in plant was highly correlated to added organic matter, which was an additional source of nitrogen available to the plant. The treatments receiving the higher plant residue application rates also resulted in greater amount of total nitrogen in the plant tissue (Table 4.6). Plant residue addition plays a more important role in nitrogen content in rice plant as compared to potassium and water management treatments. The treatment receiving higher potassium application had significantly lower nitrogen content (%) than the treatment without potassium application at flowering and maturity stages. Percent nitrogen in plant tissue decreased with age of
Figure 4.5 Effect of rice straw application and water management treatments on the ratio of panicle per stem dry weight. Alt. F/D = alternately flooded and drained, Con. F = continuously flooded.
Figure 4.6  Effect of rice straw application and water management treatments on the ratio of shoot per root dry weight. Alt. F/D = alternately flooded and drained, Con. F = continuously flooded.
Figure 4.7 Effect of rice straw application on percent unfilled grain weight average over potassium treatments from four replications under alternately flooded and drained (Alt. F/D), and continuously flooded (Con. F) treatments.
Table 4.5 Effect of rice straw application on distribution of $^{15}$N (%) labeled at different growth stages.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha$^{-1}$)</th>
<th>Tillering K 0</th>
<th>Tillering K 80</th>
<th>Panicle initiation K 0</th>
<th>Panicle initiation K 80</th>
<th>Flowering K 0</th>
<th>Flowering K 80</th>
<th>Maturity K 0</th>
<th>Maturity K 80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt. Flooded and Drained</td>
<td>0</td>
<td>1.52 ab</td>
<td>1.61 a</td>
<td>2.61 b</td>
<td>2.73 a</td>
<td>1.93 a</td>
<td>2.08 a</td>
<td>1.84 a</td>
<td>1.86 a</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.64 ab</td>
<td>1.66 a</td>
<td>2.49 a</td>
<td>2.61 ab</td>
<td>1.83 ab</td>
<td>2.01 ab</td>
<td>1.76 a</td>
<td>1.74 a</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.35 b</td>
<td>1.29 b</td>
<td>2.43 a</td>
<td>2.48 b</td>
<td>1.78 b</td>
<td>1.90 b</td>
<td>1.79 a</td>
<td>1.75 a</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>1.09 c</td>
<td>1.16 b</td>
<td>2.10 b</td>
<td>2.05 c</td>
<td>1.54 c</td>
<td>1.60 c</td>
<td>1.54 b</td>
<td>1.40 b</td>
</tr>
<tr>
<td>Con. Flooded</td>
<td>0</td>
<td>1.66 a</td>
<td>1.53 a</td>
<td>2.64 a</td>
<td>2.63 a</td>
<td>2.07 a</td>
<td>2.07 a</td>
<td>1.85 a</td>
<td>1.84 a</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.63 a</td>
<td>1.45 a</td>
<td>2.57 a</td>
<td>2.41 b</td>
<td>1.96 a</td>
<td>1.80 b</td>
<td>1.76 ab</td>
<td>1.83 a</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.32 b</td>
<td>1.34 a</td>
<td>2.34 b</td>
<td>2.37 b</td>
<td>1.80 b</td>
<td>1.79 b</td>
<td>1.67 b</td>
<td>1.78 a</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.95 c</td>
<td>0.95 b</td>
<td>1.80 c</td>
<td>1.72 c</td>
<td>1.41 c</td>
<td>1.39 c</td>
<td>1.30 c</td>
<td>1.48 b</td>
</tr>
<tr>
<td>CV (water)</td>
<td></td>
<td>9.2 ns</td>
<td>4.9 ns</td>
<td>7.1 ns</td>
<td>4.3 ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV (K)</td>
<td></td>
<td>11.3 ns</td>
<td>5.1 ns</td>
<td>4.9 ns</td>
<td>7.5 ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV (rice straw)</td>
<td></td>
<td>11.3 **</td>
<td>6.5 **</td>
<td>5.6 **</td>
<td>4.8 **</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level.

ns = non significant, *= significant at 5% level, **= significant at 1% level.
Table 4.6 Effect of rice straw application on nitrogen content (%) in rice plant at different growth stages.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha⁻¹)</th>
<th>Tillering</th>
<th>Panicle initiation</th>
<th>Flowering</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
</tr>
<tr>
<td>Alt. Flooded</td>
<td>0</td>
<td>3.72 a</td>
<td>3.37 b</td>
<td>1.85 a</td>
<td>1.56 a</td>
</tr>
<tr>
<td>and Drained</td>
<td>4</td>
<td>3.58 a</td>
<td>3.75 ab</td>
<td>1.73 a</td>
<td>2.00 a</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.88 a</td>
<td>3.65 ab</td>
<td>2.26 a</td>
<td>1.94 a</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>3.74 a</td>
<td>4.15 a</td>
<td>2.12 a</td>
<td>1.80 a</td>
</tr>
<tr>
<td>Con. Flooded</td>
<td>0</td>
<td>3.18 b</td>
<td>3.08 c</td>
<td>1.82 b</td>
<td>1.83 b</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.45 b</td>
<td>3.56 bc</td>
<td>1.87 b</td>
<td>1.90 ab</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.61 b</td>
<td>4.27 a</td>
<td>2.91 a</td>
<td>2.43 a</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>4.77 a</td>
<td>3.81 ab</td>
<td>2.57 a</td>
<td>2.49 a</td>
</tr>
</tbody>
</table>

CV (water)          | 10.3 ** | 17.1 ns  | 9.6 ns  | 14.1 ns  |
CV (K)              | 23.2 ns | 16.0 ns  | 11.2 * | 10.6 **  |
CV (rice straw)     | 11.5 ** | 19.0 **  | 7.3 ** | 17.0 *   |

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level.
ns = non significant. * = significant at 5% level, ** = significant at 1% level.
Plant. Total nitrogen in plant was highest (3-4 %) at tillering and decreasing when reaching maturity (0.4-0.5 %).

Plant nitrogen (%) derived from fertilizer (% ndff). Ndff is the fraction of N in the plant derived from the $^{15}$N labeled fertilizer. The formula for calculation %ndff is followed the method of Zapata (1990); (% $^{15}$N atom excess plant sample / % $^{15}$N atom excess labeled fertilizer) x 100. The %ndff of both the alternately flooded and drained treatment and continuously flooded treatment was highly correlated (p <0.05) to rates of plant residue application (Table 4.7). Higher plant residue application rates resulted in significantly (p < 0.01) lower ndff in both potassium application rates. No significant difference of ndff was found in potassium treatments. The ndff of the alternately flooded and drained treatment was greater than the continuously flooded treatment at panicle initiation stage and in the root. The highest ndff was found at panicle initiation stage and the lowest ndff was found in rice root in both water management treatments.

Plant Nitrogen (%) derived from soils (%ndfs). Ndfs is the fraction of N in the plant derived from soil. Assuming the crop had only two sources of nutrients the % N derived from the soil is obtained by difference as %Ndfs = 100 - %Ndff. Under both water management treatments had similar trends of ndff (Table 4.8). Ndfs was highly related to plant residue application rate as ndff but was in the opposite direction. The ndfs in treatment with higher plant residue rate was significantly higher than the treatment receiving lower rate of plant residue addition. At panicle initiation stage, amount of ndfs (%) was less than the other growth stages. Rice root was the plant tissue that received the largest portion % of nitrogen from soil nitrogen rather than fertilized nitrogen.
Table 4.7 Effect of rice straw, potassium, and water management treatments on nitrogen derived from fertilizer (%ndff) at different growth stages.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Tiller (K 0)</th>
<th>Panicle Initiation (K 0)</th>
<th>Flowering (K 0)</th>
<th>Maturity (K 0)</th>
<th>Grain (K 0)</th>
<th>Root (K 0)</th>
<th>Rice straw (t ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt. Flooded and Drained</td>
<td>0</td>
<td>44 ab</td>
<td>47 a</td>
<td>85 a</td>
<td>90 a</td>
<td>60 a</td>
<td>65 a</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>48 a</td>
<td>49 a</td>
<td>81 a</td>
<td>85 ab</td>
<td>56 ab</td>
<td>63 ab</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>37 b</td>
<td>35 b</td>
<td>78 a</td>
<td>80 b</td>
<td>54 b</td>
<td>58 b</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>27 c</td>
<td>30 b</td>
<td>66 b</td>
<td>64 c</td>
<td>45 c</td>
<td>47 c</td>
</tr>
<tr>
<td>Continuously Flooded</td>
<td>0</td>
<td>49 a</td>
<td>44 a</td>
<td>86 a</td>
<td>86 a</td>
<td>65 a</td>
<td>65 a</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>48 a</td>
<td>41 a</td>
<td>84 a</td>
<td>77 b</td>
<td>60 a</td>
<td>55 b</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>36 b</td>
<td>37 a</td>
<td>75 b</td>
<td>76 b</td>
<td>54 b</td>
<td>54 b</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>22 c</td>
<td>22 b</td>
<td>54 c</td>
<td>51 c</td>
<td>39 c</td>
<td>39 c</td>
</tr>
<tr>
<td>CV (water)</td>
<td>15.9 ns</td>
<td>11.4 **</td>
<td>9.1 ns</td>
<td>10.8 ns</td>
<td>14.0 ns</td>
<td>30.0 *</td>
<td></td>
</tr>
<tr>
<td>CV (K)</td>
<td>15.4 ns</td>
<td>6.0 ns</td>
<td>6.1 ns</td>
<td>9.5 ns</td>
<td>5.6 ns</td>
<td>25.2 ns</td>
<td></td>
</tr>
<tr>
<td>CV (rice straw)</td>
<td>15.4 **</td>
<td>7.7 **</td>
<td>7.1 **</td>
<td>6.1 **</td>
<td>7.1 **</td>
<td>18.2 **</td>
<td></td>
</tr>
</tbody>
</table>

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level. ns = non significant, * = significant at 5% level, ** = significant at 1% level.
Table 4.8 Effect of rice straw, potassium, and water management treatments on nitrogen derived from soil (ndfs) at different growth stages (%).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha⁻¹)</th>
<th>Tillering</th>
<th>Panicle initiation</th>
<th>Flowering</th>
<th>Maturity</th>
<th>Grain</th>
<th>Root</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
</tr>
<tr>
<td>Alt. Flooded and Drained</td>
<td>0</td>
<td>56 bc</td>
<td>53 b</td>
<td>15 b</td>
<td>10 c</td>
<td>40 c</td>
<td>35 c</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>52 c</td>
<td>51 b</td>
<td>19 b</td>
<td>15 bc</td>
<td>44 bc</td>
<td>37 bc</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>63 b</td>
<td>65 a</td>
<td>22 b</td>
<td>20 b</td>
<td>46 b</td>
<td>42 b</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>73 a</td>
<td>70 a</td>
<td>34 a</td>
<td>36 a</td>
<td>55 a</td>
<td>53 a</td>
</tr>
<tr>
<td>Continuously Flooded</td>
<td>0</td>
<td>51 c</td>
<td>56 b</td>
<td>14 c</td>
<td>14 c</td>
<td>35 c</td>
<td>35 c</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>52 c</td>
<td>59 b</td>
<td>16 c</td>
<td>23 b</td>
<td>40 c</td>
<td>45 b</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>64 b</td>
<td>63 b</td>
<td>25 b</td>
<td>24 b</td>
<td>46 b</td>
<td>46 b</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>78 a</td>
<td>78 a</td>
<td>46 a</td>
<td>49 a</td>
<td>61 a</td>
<td>61 a</td>
</tr>
<tr>
<td>CV (water)</td>
<td>10.0 ns</td>
<td>36.5 **</td>
<td>11.1 ns</td>
<td>11.1 ns</td>
<td>11.4 ns</td>
<td>8.6 *</td>
<td></td>
</tr>
<tr>
<td>CV (K)</td>
<td>9.7 ns</td>
<td>19.1 ns</td>
<td>7.4 ns</td>
<td>9.8 ns</td>
<td>5.0 ns</td>
<td>7.3 ns</td>
<td></td>
</tr>
<tr>
<td>CV (rice straw)</td>
<td>9.7 **</td>
<td>24.7 **</td>
<td>8.6 **</td>
<td>6.2 **</td>
<td>5.8 **</td>
<td>5.2 **</td>
<td></td>
</tr>
</tbody>
</table>

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level. ns = non significant, * = significant at 5% level, ** = significant at 1% level.
Nitrogen utilization or uptake by rice was related to organic matter rates and water management treatment (Table 4.9). The utilization of nitrogen at the tillering stage in the alternately flooded and drained treatment increased with increasing rate of plant residue addition. Nitrogen uptake was less in the continuously flooded treatment with increasing rates of plant residue application compared with the alternately flooded and drained treatment. There was no significant difference in nitrogen utilization at panicle initiation stage among the water management, potassium, and plant residue treatments. At flowering and maturity stages, nitrogen utilization increased in response to the higher organic matter application rates for both potassium and water management treatments. The higher potassium application rate (80 kg ha\(^{-1}\)) resulted in less nitrogen utilization compared with the treatment without potassium. The highest nitrogen level in rice was in grain in both water management treatments but there was no relationship to the plant residue application. Nitrogen uptake by root increased with increasing plant residue addition for both water management treatments. Potassium addition and water management treatments had no influence on nitrogen in plant root.

Analysis showing soil chemical properties for the different treatments at harvesting stage are shown in Table 4.10. Soil pH increased slightly in response to the high plant residue application rate in both the potassium and water management treatments. Soil potassium, organic matter and sodium were positively related to the amount of plant residue and rate of potassium application. There was no relationship either phosphorus or iron with plant residue levels.

4.3.4 Nutrient Uptake

At the tillering stage, nitrogen uptake by the rice plant in the alternately flooded
Table 4.9 Effect of rice straw, potassium, and water management treatments on nitrogen utilization at different growth stages (%).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha⁻¹)</th>
<th>Tillering</th>
<th>Panicle initiation</th>
<th>Flowering</th>
<th>Maturity</th>
<th>Grain</th>
<th>Root</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt. Flooded and Drained</td>
<td>0</td>
<td>2.59 a</td>
<td>1.77 ab</td>
<td>3.21 b</td>
<td>3.05 a</td>
<td>4.43 a</td>
<td>3.74 b</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.24 a</td>
<td>1.91 ab</td>
<td>3.10 b</td>
<td>4.33 a</td>
<td>3.90 a</td>
<td>3.78 b</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.89 a</td>
<td>1.28 b</td>
<td>4.76 a</td>
<td>4.32 a</td>
<td>3.57 a</td>
<td>5.26 ab</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>2.09 a</td>
<td>2.36 a</td>
<td>4.38 ab</td>
<td>4.35 a</td>
<td>5.00 a</td>
<td>5.50 a</td>
</tr>
<tr>
<td>Continuously Flooded</td>
<td>0</td>
<td>2.07 a</td>
<td>1.41 a</td>
<td>4.93 a</td>
<td>3.77 a</td>
<td>3.81 a</td>
<td>3.72 a</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.16 a</td>
<td>1.31 a</td>
<td>3.18 b</td>
<td>3.32 a</td>
<td>3.41 a</td>
<td>3.44 a</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.91 b</td>
<td>0.73 a</td>
<td>4.23 ab</td>
<td>3.92 a</td>
<td>3.56 a</td>
<td>2.75 a</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.49 b</td>
<td>0.59 a</td>
<td>3.12 b</td>
<td>3.03 a</td>
<td>5.00 a</td>
<td>3.75 a</td>
</tr>
</tbody>
</table>

CV (water) 16.5 ** 28.8 ns 32.3 * 28.8 ** 16.6 ** 26.0 ns
CV (K) 47.2 ns 23.7 ns 21.3 ns 22.4 ** 43.5 ns 40.2 ns
CV (rice straw) 33.5 ** 26.7 ns 27.5 * 26.2 ** 31.7 ns 35.8 *

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level.
ns = non significant, * = significant at 5% level, ** = significant at 1% level.
Table 4.10 Soil chemical properties at harvest.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha⁻¹)</th>
<th>pH</th>
<th>O.M. (%)</th>
<th>Bray II P (ppm)</th>
<th>K (ppm)</th>
<th>Na (ppm)</th>
<th>Fe (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
</tr>
<tr>
<td>Alt. Flooded and Drained</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>6.84 a</td>
<td>7.03 a</td>
<td>1.31 b</td>
<td>1.42 a</td>
<td>58 a</td>
<td>21 b</td>
<td>106 b</td>
</tr>
<tr>
<td>4</td>
<td>6.90 a</td>
<td>6.90 a</td>
<td>1.52 a</td>
<td>1.45 a</td>
<td>64 a</td>
<td>22 b</td>
<td>129 b</td>
</tr>
<tr>
<td>8</td>
<td>6.75 a</td>
<td>6.79 ab</td>
<td>1.50 a</td>
<td>1.53 a</td>
<td>81 a</td>
<td>25 b</td>
<td>133 b</td>
</tr>
<tr>
<td>16</td>
<td>6.83 a</td>
<td>6.53 b</td>
<td>1.56 a</td>
<td>1.51 a</td>
<td>68 a</td>
<td>35 a</td>
<td>133 b</td>
</tr>
<tr>
<td>Continuously Flooded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>6.93 a</td>
<td>6.83 a</td>
<td>1.33 b</td>
<td>1.39 a</td>
<td>58 a</td>
<td>23 c</td>
<td>147 b</td>
</tr>
<tr>
<td>4</td>
<td>6.97 a</td>
<td>6.93 a</td>
<td>1.34 b</td>
<td>1.39 a</td>
<td>49 a</td>
<td>29 bc</td>
<td>170 b</td>
</tr>
<tr>
<td>8</td>
<td>7.13 a</td>
<td>6.82 a</td>
<td>1.52 a</td>
<td>1.31 a</td>
<td>67 a</td>
<td>44 a</td>
<td>171 b</td>
</tr>
<tr>
<td>16</td>
<td>7.16 a</td>
<td>7.02 a</td>
<td>1.59 a</td>
<td>1.35 a</td>
<td>58 a</td>
<td>36 ab</td>
<td>212 a</td>
</tr>
<tr>
<td>CV (water)</td>
<td></td>
<td>3.8 **</td>
<td>3.7 **</td>
<td>21.0 *</td>
<td>20.6 **</td>
<td>6.5 **</td>
<td>10.9 *</td>
</tr>
<tr>
<td>CV (K)</td>
<td></td>
<td>2.8 ns</td>
<td>9.2 ns</td>
<td>20.3 *</td>
<td>17.8 **</td>
<td>13.6 *</td>
<td>14.0 ns</td>
</tr>
<tr>
<td>CV (rice straw)</td>
<td></td>
<td>2.6 **</td>
<td>7.6 **</td>
<td>26.4 ns</td>
<td>20.7 **</td>
<td>13.2 **</td>
<td>8.8 *</td>
</tr>
</tbody>
</table>

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level. ns = non significant, * = significant at 5% level, ** = significant at 1% level.
and drained was significantly greater (p <0.05) than uptake under continuous flooded conditions. Nitrogen uptake was highly correlated with plant residue application rates (Table 4.11). The highest nitrogen uptake by rice plants in the alternately flooded and drained treatment occurred at the highest rate of plant residue addition, whereas the highest rate of plant residue application resulted in the lowest plant nitrogen uptake in the continuously flooded treatment. There was no effect on potassium levels on nitrogen uptake by rice except at maturity. Soil treatments without added potassium had a higher nitrogen uptake compared with soil treatment with potassium addition. Increasing plant residue application rate had no effect on total nitrogen uptake at the panicle initiation stage in the continuously flooded treatment. In contrast, the higher rate of plant residue addition resulted in greater nitrogen uptake at panicle initiation stage for the alternately flooded and drained treatment. Nitrogen uptake was highly related to rate of plant residue application at flowering and maturity stage. Increasing the plant residue rate resulted in greater nitrogen uptake in both water management treatments.

The nutrient uptake study also focused on other elements, which could be influenced by the treatments. Plant tissue elements, P, K, S, Zn, Al, Fe, and Mn were analyzed only at panicle initiation stage (Table 4.12 and Table 4.13).

Phosphorus content (%) and uptake (mg pot\(^{-1}\)) by rice were strongly influenced by plant residue addition. Higher amount of P in plant tissue was found in rice grown under the high levels of plant residue treatment. The continuously flooded treatment had significantly higher P concentration and P uptake than the alternately flooded and drained treatment (p <0.05). Potassium had no effect on P uptake or plant tissue P level.

Potassium content in the plant tissue (%) and total uptake (mg pot\(^{-1}\)) by rice was
Table 4.11 Effect of rice straw, potassium, and water management treatments on nitrogen uptake (mg pot⁻¹) at different growth stages.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha⁻¹)</th>
<th>Tillering K0</th>
<th>Tillering K80</th>
<th>Panicle initiation K0</th>
<th>Panicle initiation K80</th>
<th>Flowering K0</th>
<th>Flowering K80</th>
<th>Maturity K0</th>
<th>Maturity K80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt. Flooded and Drained</td>
<td>0</td>
<td>93 ab</td>
<td>59 b</td>
<td>118 b</td>
<td>108 b</td>
<td>235 b</td>
<td>182 b</td>
<td>117 c</td>
<td>104 b</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>75 b</td>
<td>62 b</td>
<td>121 b</td>
<td>163 ab</td>
<td>221 b</td>
<td>191 b</td>
<td>146 bc</td>
<td>128 b</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>79 b</td>
<td>55 b</td>
<td>194 a</td>
<td>171 ab</td>
<td>210 b</td>
<td>288 a</td>
<td>184 bc</td>
<td>114 b</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>118 a</td>
<td>123 a</td>
<td>213 a</td>
<td>215 a</td>
<td>355 a</td>
<td>374 a</td>
<td>249 a</td>
<td>181 a</td>
</tr>
<tr>
<td>Continuously Flooded</td>
<td>0</td>
<td>68 a</td>
<td>49 a</td>
<td>182 a</td>
<td>140 a</td>
<td>187 b</td>
<td>183 b</td>
<td>89 b</td>
<td>96 b</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>71 a</td>
<td>50 a</td>
<td>121 a</td>
<td>136 a</td>
<td>177 b</td>
<td>206 ab</td>
<td>100 b</td>
<td>90 b</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>39 b</td>
<td>32 a</td>
<td>175 a</td>
<td>164 a</td>
<td>209 b</td>
<td>162 b</td>
<td>125 b</td>
<td>86 b</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>35 b</td>
<td>39 a</td>
<td>187 a</td>
<td>189 a</td>
<td>399 a</td>
<td>301 a</td>
<td>229 a</td>
<td>160 a</td>
</tr>
</tbody>
</table>

CV (water) 31.7 ** 26.2 ns 29.1 ns 27.3 ns
CV (K) 39.1 ns 30.0 ns 27.3 ns 23.7 **
CV (rice straw) 28.2 ** 27.4 ** 27.6 ** 24.6 **

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level.
ns = non significant, * = significant at 5% level, ** = significant at 1% level.
Table 4.12 Effect of rice straw, potassium, and water management treatments on plant nutrient content at panicle initiation stage.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha⁻¹)</th>
<th>P (%)</th>
<th>K (%)</th>
<th>S (%)</th>
<th>Zn (ppm)</th>
<th>Al (ppm)</th>
<th>Fe (ppm)</th>
<th>Mn (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
<td>K 0</td>
<td>K 80</td>
</tr>
<tr>
<td>Alt. Flooded and Drained</td>
<td>0</td>
<td>0.31 b</td>
<td>0.33 a</td>
<td>1.23 c</td>
<td>1.89 b</td>
<td>0.14 c</td>
<td>0.15 c</td>
<td>38 b</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.33 b</td>
<td>0.35 a</td>
<td>1.63 b</td>
<td>2.20 b</td>
<td>0.15 c</td>
<td>0.16 bc</td>
<td>45 a</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.38 a</td>
<td>0.37 a</td>
<td>2.26 a</td>
<td>2.59 a</td>
<td>0.20 a</td>
<td>0.19 a</td>
<td>50 a</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.35 ab</td>
<td>0.36 a</td>
<td>2.48 a</td>
<td>2.68 a</td>
<td>0.18 b</td>
<td>0.18 ab</td>
<td>43 ab</td>
</tr>
<tr>
<td>Continuously Flooded</td>
<td>0</td>
<td>0.33 b</td>
<td>0.35 b</td>
<td>1.34 d</td>
<td>2.14 b</td>
<td>0.14 c</td>
<td>0.15 b</td>
<td>42 b</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.38 a</td>
<td>0.39 a</td>
<td>1.93 c</td>
<td>2.45 b</td>
<td>0.17 b</td>
<td>0.17 b</td>
<td>49 a</td>
</tr>
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<td>0.40 a</td>
<td>2.64 b</td>
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<td>0.20 a</td>
<td>0.20 a</td>
<td>51 a</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.42 a</td>
<td>0.39 a</td>
<td>3.03 a</td>
<td>3.21 a</td>
<td>0.19 a</td>
<td>0.21 a</td>
<td>50 a</td>
</tr>
</tbody>
</table>

CV (water) 7.5 **
CV (K) 12.1 ns
CV (rice straw) 8.2 **

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level.

ns = non significant, * = significant at 5% level, ** = significant at 1% level.
Table 4.13 Effect of rice straw, potassium, and water management treatments on plant nutrient uptake (mg pot$^{-1}$) at panicle initiation stage.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice straw (t ha$^{-1}$)</th>
<th>P</th>
<th>K</th>
<th>S</th>
<th>Zn</th>
<th>Al</th>
<th>Fe</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K0</td>
<td>K80</td>
<td>K0</td>
<td>K80</td>
<td>K0</td>
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<td>K0</td>
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<tr>
<td>Alt. Flooded</td>
<td>0</td>
<td>18</td>
<td>b</td>
<td>19</td>
<td>a</td>
<td>70</td>
<td>c</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>18</td>
<td>b</td>
<td>20</td>
<td>a</td>
<td>92</td>
<td>b</td>
<td>124</td>
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<td>21</td>
<td>a</td>
<td>21</td>
<td>a</td>
<td>128</td>
<td>a</td>
<td>147</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>20</td>
<td>ab</td>
<td>20</td>
<td>a</td>
<td>140</td>
<td>a</td>
<td>152</td>
</tr>
<tr>
<td>and Drained</td>
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<td></td>
</tr>
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<td>0</td>
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<td>b</td>
<td>20</td>
<td>b</td>
<td>76</td>
<td>d</td>
<td>121</td>
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<tr>
<td></td>
<td>4</td>
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<td>b</td>
<td>170</td>
</tr>
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<td>ab</td>
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<td>a</td>
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<td>0</td>
<td>19</td>
<td>b</td>
<td>20</td>
<td>b</td>
<td>76</td>
<td>d</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>22</td>
<td>a</td>
<td>22</td>
<td>ab</td>
<td>109</td>
<td>c</td>
<td>139</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>23</td>
<td>a</td>
<td>23</td>
<td>a</td>
<td>149</td>
<td>b</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>24</td>
<td>a</td>
<td>22</td>
<td>ab</td>
<td>172</td>
<td>a</td>
<td>182</td>
</tr>
<tr>
<td>CV (water)</td>
<td></td>
<td>8.1 **</td>
<td>7.8 **</td>
<td>9.8 **</td>
<td>10.0 **</td>
<td>41.0 ns</td>
<td>47.6 **</td>
<td>18.6 ns</td>
</tr>
<tr>
<td>CV (K)</td>
<td></td>
<td>11.9 ns</td>
<td>10.6 **</td>
<td>12.9 ns</td>
<td>8.2 *</td>
<td>14.8 ns</td>
<td>10.9 ns</td>
<td>5.2 ns</td>
</tr>
<tr>
<td>CV (rice straw)</td>
<td></td>
<td>8.2 **</td>
<td>10.4 **</td>
<td>9.2 **</td>
<td>10.4 **</td>
<td>24.9 **</td>
<td>38.8 **</td>
<td>15.3 ns</td>
</tr>
</tbody>
</table>

Average of four replications. In the column of each water management treatment, means followed by a common letter are not significantly different at the 5% level. ns = non significant, * = significant at 5% level, ** = significant at 1% level.
also influenced by plant residue levels, potassium application rates, and water
management treatments. Added plant residue rates increased both amount of potassium in
plant tissue and uptake in both water management treatments. The application at 80 kg K
ha\(^{-1}\) resulted in significant increase in potassium content of plant tissue and total
potassium uptake. Water management treatments also significantly influence on the
content and uptake of potassium by rice. Continuously flooded treatment had greater
potassium uptake in plant tissue than the alternately flooded and drained treatment.

Plant sulfur content (%) and uptake (mg pot\(^{-1}\)) by rice plant were highly correlated
to plant residue content in soil. The higher soil plant residue resulted in an increase in
both plant sulfur content and sulfur uptake. The continuously flooded treatment resulted
in slightly greater amount of plant tissue sulfur and sulfur uptake than rice grown under
the alternately flooded and drained treatment. Potassium addition had no effect on sulfur
uptake in rice.

Zinc uptake by rice in the treatment was correlated with plant residue addition,
potassium levels, and water management treatments. Higher rates of plant residue
resulted in higher zinc tissue content and uptake. Added potassium at 80 kg ha\(^{-1}\) resulted
in lowered both zinc content and uptake. Zinc tissue level and uptake by rice in the
continuously flooded treatment was higher than the alternately flooded and drained
treatment.

Aluminum uptake by rice grown in the high plant residue treatment rates was
greater than that of rice grown in lower plant residue rates under both potassium and
water management treatments. Potassium application and water management treatments
had no effect on aluminum uptake by rice.
Iron in rice tissue was highly correlated with plant residue application rates and water management treatments. A greater amount of iron was found in rice tissue at the high plant residue application treatment compared with lower plant residue treatments under both potassium and water management treatments. Continuously flooded treatment resulted in higher iron uptake than rice grown under alternately flooded and drained treatment. Potassium levels had no effect on amount of iron in the rice plant under both water management treatments.

Manganese in plant tissue increased slightly in the alternately flooded and drained treatment with increasing plant residue levels but it was not significantly different. In the continuously flooded treatment, manganese content tended to decrease with increasing plant residue application rates. Potassium application and water management treatments had no effect on manganese uptake by rice.

4.3.5 Methane and Nitrous Oxide Emission

There was only a small amount of methane emission at 0, 1, and 4 days after planting among the treatments. The emission, however, was not significantly different among the plant residue application rates and water management treatments. In the alternately flooded and drained treatment, peaks of methane emission occurred between the second and fifth weeks after planting (Fig. 4.8). Methane emission rate was highly correlated to plant residue application rates. Methane emission from the high plant residue application treatments was significantly greater ($p < 0.05$) than that of the lower plant residue treatments at one, two, four, and five weeks following planting. The highest methane emission rate was observed in the treatment when 16 t ha$^{-1}$ of plant residue
applied and the lowest methane emission rate was detected in the treatment without an added plant residue.

In the continuously flooded treatment, the general trend or pattern of methane emission was the same as in the alternately flooded and drained treatment (Fig. 4.9). However, the total amount of methane evolved from the continuously flooded treatment was greater than that of the alternately flooded and drained treatment during most sampling period. The high plant residue application treatments at 16 t ha\(^{-1}\) under continuously flooded treatment (54 kg per ha per day) emitted approximately twofold as much methane as the alternately flooded and drained treatment (23 kg per ha per day) at about two weeks after planting. At one week after planting, significant methane emission was observed at all plant residue treatments under both water management treatments. Slightly greater methane emission was measured under the higher plant residue treatment under both water management treatments.

Total methane emissions for the treatments entire the growing season (calculated by integrating the area under the line graph) are shown in Fig 4.10. Total methane emission under the two water management treatments was not significantly different at the low rate of plant residue treatments (0 and 4 t ha\(^{-1}\)). Increasing added plant residue to 8 t ha\(^{-1}\) the total emission from continuous flooded treatment was slightly higher than that of the alternately flooded and drained treatment. The total emission in the continuously flooded treatment was approximately two times greater than that of the alternately flooded and drained when plant residue application rate reached 16 t ha\(^{-1}\).

Nitrous oxide emission was very low (less than one kg ha\(^{-1}\) d\(^{-1}\)) compared with methane emission. At the beginning of the treatment, the emission of nitrous oxide was
Figure 4.8 Effect of rice straw on methane emission of the alternately flooded and drained treatment (F/D). 0, 4, 8, and 16 = rice straw incorporation rates (t ha$^{-1}$).
Figure 4.9 Effect of rice straw on methane emission of the continuously flooded treatment (F). 0, 4, 8, and 16 = rice straw incorporation rates (t ha\(^{-1}\)).
Figure 4.10 Methane emission entire season (calculated from the integration of the area under the line chart Fig 4.8 and Fig 4.9), Alt. F/D = alternately flooded and drained, Con. F = continuously flooded.
highest in the lowest plant residue rate in both water management treatments, especially at 0, 1, and 4 days after planting. From 1 week after planting to harvesting, the amount of nitrous oxide emission was constant low and was in the same level as of the atmosphere concentration. Plant residue had no affected on nitrous oxide emission in both water management treatments.

4.4 CONCLUSIONS AND SUGGESTIONS

Soil pH decreased slightly at an increased rate of plant residue in both water management treatments. The soil pH in continuously flooded treatment fluctuated some during the first week after planting. However, soil pH in both water management treatments was fairly constant from the third week until harvesting and was not affected by the rate of plant residue application. Soil redox potential was correlated to plant residue levels. The lowest soil redox potential (-278 mV) was measured in the highest plant residue rate (16 t ha\(^{-1}\)) in both water management treatments. The expected high redox potential of the alternately flooded and drained treatment was not observed in the experiment. This was attributed to draining of surface water in the pots in this experiment. Even though the soil surface in the pots was dried, the moisture in the soil at the depth below 10 cm remained saturated.

Alternating flooded and drained cycles in the rice field for some periods of time significantly increased plant growth. This is attributed to the reduction of the toxic elements and some toxic intermediate organic acids (that occurred during decomposition of plant residue), and increases in the availability of some nutrients resulting from the mineralization of organic nitrogen during this period.
The labeled $^{15}$N fertilizer nitrogen experiment showed that nitrogen was very important to rice growth. At panicle initiation stage nitrogen in rice plant was derived mostly from fertilizer (high value of %ndff). Plant residue also served as a significant source of nitrogen to the rice plants. Therefore, application of nitrogen fertilizer in this period should be considered soil plant residue content and time of application.

The uptake of phosphorus, potassium, zinc, and iron was greater in continuously flooded treatment, whereas uptake of sulfur was higher in alternately flooded and drained treatment. The uptake of aluminum and manganese was not related to water management treatments. Generally, the uptake of these nutrients increased with increasing plant residue rate.

Methane emission from flooded rice soil was significantly correlated with rice straw levels. Higher rate of rice straw in soil enhanced methane emission more than the lower rate of rice straw in both water management treatments. Methane emission in the alternately flooded and drained treatment was less than that of continuously flooded treatment, especially at the 16 t ha$^{-1}$ rice straw applied, which methane emission was 668, and 1400 kg- ha season$^{-1}$, respectively. Thus, draining the rice field for some period of time could be a feasible method to reduce methane production in wetland rice production.

This greenhouse studies has answered some important questions regarding the relationship of soil rice straw level on rice growth. Further studies should be conducted under field conditions which the draining period should be extended longer than that used in this pot experiment. The levels of rice straw application should be increased to a higher levels in order to reflect the potential of high plant residue found in rice fields of Southern Louisiana where stunted or poor rice growth has been documented.
CHAPTER 5

EFFECT OF RICE STRAW INCORPORATION AND WATER MANAGEMENT PRACTICES ON METHANE EMISSION AND RICE PRODUCTIVITY: FIELD EXPERIMENT

5.1 INTRODUCTION

Globally irrigated rice is grown on about 50% of total harvested rice area contributing to about 70% of total rice production (IRRI, 2002). In irrigated rice system, rice is usually planted under controlled irrigation water. Since water governs several processes that are affect rice growth and development under flooded condition, water management for optimum crop yield is indispensable in rice production. Proper management of water in rice production leads to better growth and grain yield.

Rice production in the United States is grown under either water- or dry-seeded cultural systems in Arkansas, Texas, Mississippi, Missouri, and Florida (Linscombe et al., 1999; Miller and Street, 1999). In California, rice is dominantly cultured by water seeding. In Louisiana, water seeding is the predominant system. However, dry seeding also contributes significantly to total production, particularly in the northeastern region of the state (Street and Bollich, 2003).

There are three basic water management practices used in both rice cultural systems: 1) delayed flooding, 2) pinpoint flooding, and 3) continuous flooding (Street and Bollich, 2003). When a delayed flood is used, fields are drained after water seeding for an extended period, usually three to four weeks before the permanent flood is applied. This system is normally used where red rice is not a problem because it provides no red rice suppression (Linscombe et al., 1999). Pinpoint flood is the most common practice used in water seeding system, particularly in southern Louisiana. The field is drained shortly after seeding with pregerminated seed. This drain period allows time for the radical root to
penetrate the soil for better establishment. Usually a three- to five-day drainage period is adequate. The field is then permanently flooded until the rice is near maturity. This water management system is an excellent method to control red rice. Since the field is maintained in an anaerobic condition, oxygen necessary for red rice germination is deficient (Linscombe et al., 1999). Continuous flooding is used on a limited area in Louisiana. This system is similar to the pinpoint system, but no short period drain is applied. From the three water management systems, continuous flooding is the best method for red rice control, but it can reduce stand establishment. In addition, Hill et al. (1992) suggested that continuous flooding provides excellent weed control, especially when combined with herbicides.

Aeration of the soil by intermittent wetting and drying or limiting irrigation will increase oxygen supply to the soil which would result in increase CH$_4$ oxidation and a decrease in CH$_4$ formation. The use of a combination of mitigation technologies for methane emission shows great potential to maintain or even reduce CH$_4$ emission from rice fields without rice yield reduction. The adoption of direct seeding (wet and dry seeding) instead of transplanting will likely reduce CH$_4$ emission (IRRI, 1996).

Reducing the amount of water-use for wetland rice production is still controversial since there are critical issues associated with yield loss. De Datta (1981) noted that water stress at any growth stage reduces rice yield. Soil moisture content of -50 kPa (slightly above field capacity) may reduce rice grain yield by 20-25% as compared to continuously flooded treatments. Rice is most sensitive to water stress during the reproductive stage. Water shortage at this growth stage can cause yield loss by lowering sterility (Yoshida, 1981).
Plant materials are the major source of soil organic matter (SOM). SOM usually includes decomposition products at various stages of decomposition of organic materials and products synthesized by soil microorganisms (Sahrawat, 2004). SOM consisted of two types of compounds: non-humic substances, belonging to identifiable chemical compositions such as carbohydrates, and humic substances consisting of a series of brown to dark-brown, high molecular weight biopolymers (Quideau, 2002).

Mahieu et al. (2002) studied the fate of organic matter in wetland rice soils collected from different cropping patterns. The results showed that the soils with low number of crops per year (no or one rice crop) contained less C than the soils with intensive rice cropping system (2-3 rice crops per year). Furthermore, the rice soils with lower crops per season contained more free iron than that of intensive cropping soils.

Straw is the major organic material source available to most rice farmers, particularly in double- and triple- cropping systems. Rice straw has long been considered an important source of nutrient because it contains about 0.6 % N, 0.1 % each of P and S, 1.5 % K, 5 % Si, and 40 % C (Ponnampeteruma, 1984). Straw is also an important source of micronutrients for rice such as zinc (Zn), which is recommended as a fertilizer addition in some locations, and is the most important factor in maintaining the cumulative silicon (Si) balance in rice (Dobermann and Fairhurst, 2002). Rice straw plus mineral N can also enhance N fixation by increasing number of N-fixing bacteria (Ponnampeteruma, 1984).

Ponnampeteruma (1984) reported that rice straw incorporation generally resulted in increase rice grain yield than did straw removal or burning, especially if rice straw incorporation continued for a number of growing seasons. The benefit is greater in warmer climates, where toxic compounds released by decomposition of incorporated
straw had time to decompose or remove before transplanting (Cho and Ponnampereuma, 1971). In cooler climates, straw incorporation can result in lower yield in initial years but over the long-term would be beneficial because N mineralization from the straw increases rice growth and yield (Verma and Bhagat, 1992).

Rice plants can enhance CH$_4$ production and flux by providing substrates for methanogenic bacteria through the production of root litter and root exudates (Holzapfel-Pschorn et al., 1986; Sass et al., 1990) that contain carbohydrates and amino acids. Sass et al. (1990) and Whiting et al. (1991) have reported a linear relationship between plant biomass and CH$_4$ emissions. Wang et al. (1992) also found a positive correlation between CH$_4$ emission rate and straw application rate in Crowley soil up to a rate of 20 g kg$^{-1}$ (44 t ha$^{-1}$). However, Kludze and DeLaune (1995) concluded that the CH$_4$ emission rate was not always a positive relation to the rate of straw incorporation.

The production of methane from the rice field is also affected by soil physical and chemical properties. Soil properties include organic matter and nitrogen contents, cation exchange capacity, amount and form of Fe and Mn in the soil solution, soil redox potential, soil pH and soil texture (Wang et al., 1992; Lindau et al., 1993).

Data from previous experiments showed significant adverse affects of high organic matter on rice growth and grain yield. At the same time, there is a positive correlation between methane emission rate and organic matter addition. Water management techniques can be used to alleviate problems associated with organic matter as related to wetland rice production.

To verify the results from the previous pot experiments, a field experiment was conducted by using the same factors employed in the pot experiment. Potassium addition
was not included in the field experiment because the treatment did not show significant differences in grain yield and other parameters in the pot experiment. The main objectives of this field experiment were to evaluate water management techniques for maintaining grain yield and reducing methane emission in Crowley soil receiving high organic matter in the form of plant residue (rice straw).

5.2 MATERIALS AND METHODS

The experiment was conducted at the Crowley Rice Research Station, Louisiana. The soil was a Crowley silt loam (Typic albaqualf). A 2 x 5 factorial experiment was arranged in a split plot design with two water management practices as main plot treatments (alternately flooded and drained, and continuously flooded), five rates of rice straw incorporation as subplot treatment (0, 3, 6, 12, and 24 t ha\(^{-1}\)), with four replications. Plots size was 2.1 x 6 m.

Nitrogen, phosphorus and potassium were applied to soil at a rate of 100-75-75 kg ha\(^{-1}\), respectively as pre-plant incorporation and second nitrogen application was applied at 85 kg ha\(^{-1}\) (at sixth week after planting). Rice straw was incorporated to an approximately 15 cm depth at the assigned rates using a rotary tiller. Four platinum electrodes were placed in all plots at a 10 cm depth. A pH electrode was placed in only one replication of each water management main plot. Soil redox potential and pH data were recorded hourly in established plots via data loggers until harvesting.

5.2.1 Plant Growth Measurement

An area of 0.5 square meter of each plot was marked for observation of plant growth, plant sampling, and grain yield measurement. Plant height and stem number were recorded at 17, 33, 50, 64, and 110 days after planting (DAP). Plant samples were
collected from 0.5 square meters at maturity. The samples were measured for height, and weighed after drying at 65-70 °C in oven for 72 hours. Stem dry weight and grain yield were recorded. Plant stems and grain were randomly sub-sampled and ground for analysis of nutrient content in tissue.

5.2.2 Soil Sampling and Analysis

Soil samples were collected at harvest from all treatment plots using a five cm diameter plastic tube. The tube was placed on the soil surface and pressed to a 15 cm depth into the soil. Collected soil samples were air-dried and analyzed for pH, organic matter, S, P, K, Ca, Mg, Na, and Fe using the methods that are shown in Table 3.2.

5.2.3 Methane Flux Measurement

Methane emission measurements were conducted using diffusion chambers (Lindau et al., 1991). The sketch of the closed chamber system was presented in Figure 4.1. The base units were constructed of clear Plexiglas 30 x 30 x 30 cm. The removable diffusion chambers (top phase) were also constructed of the same dimensions of Plexiglas and contain a 9-volt fan mounted on the inside, which was used to mix the air column within the chamber prior to sampling. Sampling techniques were identical for each treatment. During flux measurements the base troughs were filled with water in order to seal the diffusion chambers. Pressure inside the chamber was relieved through the use of coiled 1.5-meter Tygon tubing. This theoretically maintained pressure equilibrium between the outside and inside of the chamber while minimizing any introduction of exterior gases. A rubber septum serving as a sampling port and a thermometer were also located on the top of each chamber. Additional extension pieces, constructed the same
way as the base units, were stacked as the rice grew in order to insure the chamber fit over the rice plants.

A 15 ml sample was withdrawn from the chambers using a 20 ml gas-tight syringe at 0 and 15 minute for methane flux measurement. The gas samples were injected into a silicone sealed Vacutainer. These Vacutainers were evacuated using a high-vacuum preparation line to remove residual gases (Lindau et al., 1991). Once evacuated, the tubes were sealed with silicone rubber and subsequently resealed after injecting of the sample. Floodwater heights and air temperature inside the chamber were recorded for calculation of headspace and emission rate.

Gas samples were analyzed for methane using a Shimadzu GC14-A flame ionization gas chromatograph. A gas-tight syringe was used to inject a 1.0 ml into a stainless steel column. The detector temperatures were set at 200 °C. Integration and analysis were accomplished with the use of Shimadzu R-14AC Chromatopac. Raw data was recorded and used to calculate the flux of CH₄ per unit area. A closed chamber equation (Rolston, 1986) was used to estimate methane fluxes from each treatment.

\[ F = \left( \frac{V}{A} \right) \left( \frac{(T+C)}{T} \right) \left( \frac{\Delta c}{\Delta t} \right) \]

Where:

- \( F \) = flux of methane from soil/water surface
- \( V \) = headspace volume of chamber (L)
- \( A \) = surface area (base-soil surface area)
- \( T \) = absolute temperature
- \( C \) = temperature (Celsius)
- \( (\Delta c / \Delta t) \) = change in gas concentration per unit time
5.2.4 Statistical Analysis

The data were analyzed by IRRISTAT software (IRRI, 1992). If any results from ANOVA showed significance, then mean comparisons were obtained with Duncan’s Multiple Range Test (DMRT).

5.3 RESULTS AND DISCUSSION

5.3.1 Soil pH and Eh

In the alternately flooded and drained treatment, soil pH during the first week after planting ranged between 4.9 and 6.6 (Fig 5.1). During the draining period, soil pH increased from 6.0 to 8.0. After reflooding, soil pH again decreased with less fluctuation than the previous period, ranging between 5.3-5.7. Overall soil pH of alternately flooded and drained treatments was higher in the higher organic matter treatment. With continuously flooding, soil pH during the first week (5.2-6.3) fluctuated less than that in the alternately flooded and drained treatments. The maximum pH value was measured in treatments that received organic matter at a rate of 12 t ha$^{-1}$ (Fig 5.2). The pH fluctuated widely between mid season and harvest. Soil pH of the alternately flooded and drained treatment remained constant after draining. Soil pH of continuously flooded and drained fluctuated based on the period for which the soil was flooded or drained.

Soil redox potential in the alternately flooded and drained treatment was inversely correlated with rice straw application rate (Fig 5.3). The treatment with a high organic matter had a lower Eh value than the treatments with lower levels of added organic matter. During the drainage period, soil Eh increased significantly in all organic matter application levels. Soil Eh again decreased after reflooding. Overall soil Eh was in the range of –100 to +100 mV during the draining period. In the continuously flooded
treatment, soil redox was also related to organic matter application or rice straw. In addition, the measured Eh value could be separated into two groups for the first half of the season. The first group of Eh measurement with values over 0 mV was associated with the treatment with rice straw application at 0, 3, and 6 t ha\(^{-1}\). The second group of Eh values which were below 0 mV was associated with the treatment of rice straw application rates of 12 and 24 t ha\(^{-1}\) (Fig 5.4). Overall the Eh values in the continuously flooded treatment decreased with time followed by some increases at the end of season. This was attributed to water leaking from the main plot.

5.3.2 Soil Chemical Properties

Analyses of soil collected at the end of season are presented in Table 5.1. The average soil pH of the alternately flooded and drained treatment was slightly higher than that of the continuously flooded. Soil pH of the higher straw application treatment was significantly lower (more acidity) than the treatments with less straw application for both water management treatments. Measured soil organic matter level was related to the straw application rate. The highest soil organic matter content was in the treatment receiving 24 t ha\(^{-1}\) of rice straw. The lowest soil organic matter level was in the treatments which received no added rice straw. Water management treatment had no effect on soil organic matter content. The amount of sulfur in soil was related statistically (p < 0.05) to both amount of rice straw addition and water management treatments. Soil sulfur level did not change with increasing rate as rice straw addition in the alternately flooded and drained treatment. In the continuously flooded soil treatment sulfur content decreased slightly with increasing rate of rice straw application. Soil sulfur content in the high rice straw application rate in the alternately flooded and drained treatment was
Figure 5.1 Effect of rice straw and water management treatments on soil pH in the alternately flooded and drained treatment. 0, 3, 6, 12, and 24 = rice straw incorporation rates (t ha⁻¹).
Figure 5.2 Effect of rice straw and water management treatments on soil pH in the continuously flooded treatment. 0, 3, 6, 12, and 24 = rice straw incorporation rates (t ha⁻¹).
Figure 5.3 Effect of rice straw and water management treatments on soil redox potential in the alternately flooded and drained treatment. 0, 3, 6, 12, and 24 = rice straw incorporation rates (t ha⁻¹).
Table 5.1 Effect of rice straw and water management treatments on selected soil properties.

<table>
<thead>
<tr>
<th>Rice straw (t ha⁻¹)</th>
<th>Soil pH</th>
<th>Soil O.M. (%)</th>
<th>Soil S (ppm)</th>
<th>Soil P (ppm)</th>
<th>Soil K (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.12 a</td>
<td>6.70 ab</td>
<td>1.18 c</td>
<td>1.21 d</td>
<td>19.5 a</td>
</tr>
<tr>
<td>3</td>
<td>6.83 ab</td>
<td>6.87 a</td>
<td>1.33 bc</td>
<td>1.28 cd</td>
<td>18.7 a</td>
</tr>
<tr>
<td>6</td>
<td>6.75 b</td>
<td>6.71 ab</td>
<td>1.35 b</td>
<td>1.37 bc</td>
<td>19.0 a</td>
</tr>
<tr>
<td>12</td>
<td>6.50 b</td>
<td>6.67 ab</td>
<td>1.38 b</td>
<td>1.51 b</td>
<td>18.3 a</td>
</tr>
<tr>
<td>24</td>
<td>6.48 b</td>
<td>6.48 b</td>
<td>1.73 a</td>
<td>1.72 a</td>
<td>19.1 a</td>
</tr>
</tbody>
</table>

CV/F-test

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Rice straw</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.7 ns</td>
<td>3.5 **</td>
</tr>
<tr>
<td></td>
<td>17.7 ns</td>
<td>7.7 **</td>
</tr>
<tr>
<td></td>
<td>4.9 *</td>
<td>5.2 **</td>
</tr>
<tr>
<td></td>
<td>11.6 **</td>
<td>15.8 ns</td>
</tr>
<tr>
<td></td>
<td>5.2 **</td>
<td>12.1 **</td>
</tr>
</tbody>
</table>

Average of four replications. In each column, means followed by a common letter are not significantly different at the 5% level.

ns = non significant, * = significant at 5% level, ** = significant at 1% level.

Figure 5.4 Effect of rice straw and water management treatments on soil redox potential (mV) in the continuously flooded treatment. 0, 3, 6, 12, and 24 = rice straw incorporation rates (t ha\(^{-1}\)).
slightly greater than in the continuously flooded treatment. However, it should be pointed out these difference in sulfur were not statistical different among the treatments.

Soil phosphorus was not significantly different in any level of rice straw application, but it was significantly greater in the continuously flooded than in the alternately flooded and drained treatment. Soil potassium content with higher straw application was significantly greater than in lower straw application (p < 0.05). Soil potassium content was also greater in continuously flooded than in the alternately flooded and drained treatment.

5.3.3 Nutrient Content in Rice Tissue

Plant stem nutrient content was determined at harvesting stage. The results are shown in Table 5.2. Plant tissue (stem) nitrogen content was slightly greater with higher rice straw application rates compared with the lower rice straw application rates for both water management treatments, but it was not statistically different. Nitrogen content of plant tissue in the alternately flooded and drained treatment was significantly greater (p < 0.05) than the continuously flooded treatment. Total phosphorus content and potassium content with higher straw application rates were significantly greater (p < 0.05) than with the lower rate of rice straw application. Water management treatments had no influence on neither the amount of phosphorus nor potassium content in rice tissue. Total sulfur content in the tissue was not significantly different among straw application rates and water management treatments. Total calcium in the plant with higher straw application rate was significantly (p < 0.05) lower than with the lower rate of straw application in both water treatments. The average plant content of potassium in straw application in the
Table 5.2 Effect of rice straw and water management treatments on nutrient content (%) in rice stem.

<table>
<thead>
<tr>
<th>Rice straw (t ha⁻¹)</th>
<th>Total N</th>
<th>Total P</th>
<th>Total K</th>
<th>Total S</th>
<th>Total Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.59 a</td>
<td>0.53 a</td>
<td>0.09 a</td>
<td>0.06 c</td>
<td>1.17 c</td>
</tr>
<tr>
<td>3</td>
<td>0.61 a</td>
<td>0.52 a</td>
<td>0.08 a</td>
<td>0.07 bc</td>
<td>1.34 bc</td>
</tr>
<tr>
<td>6</td>
<td>0.71 a</td>
<td>0.53 a</td>
<td>0.10 a</td>
<td>0.09 b</td>
<td>1.38 abc</td>
</tr>
<tr>
<td>12</td>
<td>0.61 a</td>
<td>0.58 a</td>
<td>0.10 a</td>
<td>0.09 b</td>
<td>1.64 ab</td>
</tr>
<tr>
<td>24</td>
<td>0.69 a</td>
<td>0.62 a</td>
<td>0.12 a</td>
<td>0.12 a</td>
<td>1.70 a</td>
</tr>
</tbody>
</table>

CV/F-test Water  19.5 ** 15.2 ns  11.4 ns  13.9 ns  12.1 **
Rice straw       13.7 ns  19.9 ** 14.0 ** 10.7 ns  12.7 **

Average of four replications. In each column, means followed by a common letter are not significantly different at the 5% level.
ns = non significant, * = significant at 5% level, ** = significant at 1% level.
Alt. F/D = alternately flooded and drained treatment, Con. F = Continuously flooded treatment
alternately flooded and drained was significantly greater (p < 0.05) than in the continuously flooded treatment.

Grain nutrient content is shown in Table 5.3. The average content of nitrogen in grain was approximately 1.05 % in the alternately flooded and drained treatment and 1.00 % in the continuously flooded treatment. Nitrogen content of the grain in the alternately flooded and drained treatment was not related to straw application rates but nitrogen content of the grain was greater in the higher straw application rate in the continuously flooded treatment. Neither straw application nor water management treatments influenced phosphorus, potassium, and calcium content of grain. Total sulfur content in the grain with alternately flooded and drained treatment was significantly greater (p < 0.05) than continuously flooded, but there was not significance different among straw application rates.

5.3.4 Nutrient Uptake in the Rice Plant

Nutrient uptake was calculated by multiplying plant dry weight with their nutrient concentration. Plant nutrient uptake by rice among the treatments is shown in Table 5.4. Total nitrogen uptake by rice was not different among rates of straw application and among water management treatments. The uptake of nitrogen by rice in alternately flooded and drained was significantly greater (p < 0.05) than in the continuously flooded treatment. Sulfur and calcium uptake were similar to nitrogen. Phosphorus and potassium uptake were significantly greater (p <0.05) at higher straw application rates compared with lower straw application treatments. In the alternately flooded and drained treatment, phosphorus and potassium uptake were significantly greater (p <0.05) than in the continuously flooded treatment.
Table 5.3 Effect of rice straw and water management treatments on nutrient content (%) in rice grain.

<table>
<thead>
<tr>
<th>Rice straw (t ha⁻¹)</th>
<th>Total N (%)</th>
<th>Total P (%)</th>
<th>Total K (%)</th>
<th>Total S (%)</th>
<th>Total Ca (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.05 a</td>
<td>0.93 c</td>
<td>0.3 a</td>
<td>0.28 a</td>
<td>0.34 a</td>
</tr>
<tr>
<td>3</td>
<td>1.05 a</td>
<td>0.96 bc</td>
<td>0.32 a</td>
<td>0.27 a</td>
<td>0.34 a</td>
</tr>
<tr>
<td>6</td>
<td>1.04 a</td>
<td>1.01 b</td>
<td>0.32 a</td>
<td>0.31 a</td>
<td>0.37 a</td>
</tr>
<tr>
<td>12</td>
<td>1.05 a</td>
<td>1.02 ab</td>
<td>0.33 a</td>
<td>0.32 a</td>
<td>0.36 a</td>
</tr>
<tr>
<td>24</td>
<td>1.04 a</td>
<td>1.07 a</td>
<td>0.3 a</td>
<td>0.32 a</td>
<td>0.36 a</td>
</tr>
</tbody>
</table>

CV/F-test           Water  6.8 * | 19.4 ns | 23.9 ns | 7.4 ** | 1.4 ns |
                    Rice straw  4.1 ns | 18.0 ns | 19.5 ns | 6.0 ns | 25.5 ns |

Average of four replications. In each column, means followed by a common letter are not significantly different at the 5% level. ns = non significant, * = significant at 5% level, ** = significant at 1% level.
Table 5.4 Effect of rice straw and water management treatments on nutrient uptake (g m⁻²) in rice stem at maturity.

<table>
<thead>
<tr>
<th>Rice straw (t ha⁻¹)</th>
<th>Total N</th>
<th>Total P</th>
<th>Total K</th>
<th>Total S</th>
<th>Total Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.83 ab</td>
<td>2.62 a</td>
<td>0.56 ab</td>
<td>0.29 c</td>
<td>7.57 c</td>
</tr>
<tr>
<td>3</td>
<td>3.45 b</td>
<td>2.20 a</td>
<td>0.46 b</td>
<td>0.28 c</td>
<td>7.74 c</td>
</tr>
<tr>
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<td>4.38 ab</td>
<td>2.47 a</td>
<td>0.60 ab</td>
<td>0.41 bc</td>
<td>8.43 bc</td>
</tr>
<tr>
<td>12</td>
<td>3.81 ab</td>
<td>3.11 a</td>
<td>0.63 ab</td>
<td>0.50 ab</td>
<td>10.33 ab</td>
</tr>
<tr>
<td>24</td>
<td>4.46 a</td>
<td>2.99 a</td>
<td>0.70 a</td>
<td>0.60 a</td>
<td>10.92 a</td>
</tr>
</tbody>
</table>

CV/F-test Water 31.9 ** 32.1 ** 16.1 ** 23.5 ** 21.9 **
Rice straw 17.9 ns 23.2 ** 18.1 ** 15.2 ns 18.3 ns

Average of four replications. In each column, means followed by a common letter are not significantly different at the 5% level.
ns = non significant, * = significant at 5% level, ** = significant at 1% level.
Total nutrient uptake by rice grain is shown in Table 5.5. Nitrogen uptake in the grain was significantly greater with higher straw application treatment than in with lower straw application. The alternately flooded and drained treatment resulted in more grain nitrogen uptake than in the continuously flooded treatment. The overall average grain P uptake in the alternately flooded and drained was slightly greater than in the continuously flooded but was not statistically different. Rice straw application rate had no significant effect on grain P uptake in either water management treatment. Grain K, Ca, and S uptake were similar to grain P uptake. Grain S uptake in the continuously flooded treatment increased with increasing rate of straw application but was not statistically different among treatments.

5.3.5 Methane Emission

The flux of methane in the alternately flooded and drained treatments is shown in Fig 5.5. Methane emission at the highest rate of straw application (24 t ha$^{-1}$) was significantly greater than with the other organic matter application rates at the second week after planting. The peak of methane emission occurred the fifth week following planting. After draining (the fourth week after planting), methane emission decreased dramatically in all rice straw application rates. After reflooding, the plot receiving the highest rate of straw application (24 t ha$^{-1}$) maintained the highest rate of methane emission throughout the growing season.

Methane emission from the continuously flooded treatment is presented in Figure 5.6. Methane emission did not differ among levels of rice straw application during the first week. Methane emission was detected at the second week in both the alternately flooded and drained and the continuously flooded treatments and higher amounts of
Table 5.5 Effect of rice straw and water management treatments on nutrient uptake in rice grain (g m\(^{-2}\)).

<table>
<thead>
<tr>
<th>Rice straw (t ha(^{-1}))</th>
<th>Total N</th>
<th>Total P</th>
<th>Total K</th>
<th>Total S</th>
<th>Total Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15.01 a</td>
<td>8.94 b</td>
<td>4.18 a</td>
<td>3.96 a</td>
<td>4.69 a</td>
</tr>
<tr>
<td>3</td>
<td>14.56 a</td>
<td>7.69 b</td>
<td>4.37 a</td>
<td>3.71 a</td>
<td>4.65 a</td>
</tr>
<tr>
<td>6</td>
<td>14.87 a</td>
<td>9.22 b</td>
<td>4.44 a</td>
<td>4.32 a</td>
<td>5.15 a</td>
</tr>
<tr>
<td>12</td>
<td>14.86 a</td>
<td>11.47 a</td>
<td>4.49 a</td>
<td>4.39 a</td>
<td>4.91 a</td>
</tr>
<tr>
<td>24</td>
<td>15.13 a</td>
<td>12.94 a</td>
<td>4.15 a</td>
<td>4.37 a</td>
<td>4.96 a</td>
</tr>
</tbody>
</table>

CV/F-test  
Water      | 17.4 ** | 18.9 ns | 24.1 ns | 10.5 ns | 20.2 ns |
Rice straw  | 9.1 **  | 18.0 ns | 19.2 ns | 6.2 ns  | 22.6 ns |

Average of four replications. In each column, means followed by a common letter are not significantly different at the 5% level. ns = non significant, * = significant at 5% level, ** = significant at 1% level.
Figure 5.5 Effect of rice straw on methane emission in the alternately flooded and drained treatment. 0, 3, 6, 12, and 24 t ha$^{-1}$ = rice straw incorporation rates.
Figure 5.6 Effect of rice straw on methane emission in the continuously flooded treatment. 0, 3, 6, 12, and 24 t ha$^{-1}$ = rice straw incorporation rates.
emission were observed at the third week. The peak of methane emission from the continuously flooded treatment occurred during the forth week after planting. After that period, methane emission decreased with time with a slightly increase in the emission at harvest time for the treatments receiving rice straw application of 12 and 24 t ha$^{-1}$. The lowest rate of emission was detected in the treatment without any added rice straw. Methane emission increased with increasing rates of rice straw in both water management treatments.

Total methane emission over the entire growing season for continuously flooded and alternately flooded and drained treatment is shown in Figure 5.7. The emission chart was plotted by integrating the area under the line chart (from Fig 5.5 and 5.6). Methane emission in the treatment with the higher rice straw additions (12 and 24 t ha$^{-1}$) was significantly greater than with the lower straw application rates. At low rates of straw application (0, 3, and 6 t ha$^{-1}$), total methane emission was less than 1,000 kg ha$^{-1}$ over the growing season. This data did not include the ratoon crop. Methane emission from the continuously flooded treatment was significantly greater than that of alternately flooded and drained treatment. The greatest emission rate was measured with the highest rice straw application rates (12 and 24 t ha$^{-1}$). Methane emission from the alternately flooded and drained treatment with rice straw applications of 0, 3 and 6 t ha$^{-1}$ was slightly lower than for the same rice straw addition in the continuously flooded treatment.

5.3.6 Plant Growth

Plant growth as influenced by rice straw incorporation rate was observed at the early rice growth stage (1-3 weeks). Following drainage, plant response in the alternately flooded and drained treatment was greener in color and more growth than in the
Figure 5.7 Effect of rice straw on methane emission per season of main crop (data were calculated by integrating the area under the line charts; Fig 5.5 and Fig 5.6). Alt. F/D = alternately flooded and drained treatment, Con. F = continuously flooded treatment.
continuously flooded treatment. Number of plants per unit area in each plot can be an important parameter in determining whether the plant was under stress from any adverse effect from the rice straw addition. Plant number observed for 5 different growth stages showed no difference among the plots (data not shown).

Plant height was measured at five growth stages of all treatments. In alternately flooded and drained treatment, plant height in the treatments received low rice straw rates (0, 3, and 6 t ha\(^{-1}\)) was higher than that of the continuously flooded treatment (Fig 5.8). However, at the higher rates of rice straw (12 and 24 t ha\(^{-1}\)) plant height in both water management treatments was not different (Fig 5.9). The treatment without rice straw had the tallest plants. Plant height in both water management treatments was not different at the first two sampling times. In both water management treatments, plant height for the 24 t ha\(^{-1}\) rice straw application treatment for the first two measurement periods was less than plant height in the other treatments. However, following drainage, plant height in the alternately flooded and drained treatment was significantly greater (p < 0.05) than the continuously flooded treatment.

5.3.7 Plant Dry Matter and Grain Yield

Dry matter obtained from 0.5 square meters sub plots are shown in Figure 5.10. Dry matter weight with the higher rice straw application rate was significantly greater (p <0.05) than with the lower rice straw application rate in the continuously flooded treatment, but there was not different of dry weight in the alternately flooded and drained treatment. The treatment without any rice straw addition in the continuously flooded treatment had similar dry matter as treatments with rice straw applied at 3 and 6 t ha\(^{-1}\). This phenomenon might have been due to rice straw having some adverse effect on
Figure 5.8 Effect of water management treatments on plant height (cm) in 2002. Alt. F/D = alternately flooded and drained treatment, and Con. F = continuously flooded treatment.
Figure 5.9 Effect of rice straw incorporation (24 t ha$^{-1}$) on plant height (cm) in 2002. Alt. F/D = alternately flooded and drained treatment, and Con. F = in the continuously flooded treatment.
growth of rice in the continuously flooded compared with the alternately flooded and
drained treatment. Rice straw application rate did not show any relationship to plant dry
matter in the alternately flooded and drained treatment but there was a significant
difference (p <0.05) in plant dry matter for the continuously flooded treatment. Dry
matter weight in the alternately flooded and drained treatment was significantly greater
than in the continuously flooded treatment (p <0.01).

Grain weight collected from 0.5 m² showed significant difference among both rice
straw application treatment and water management treatment (Figure 5.11). In the
continuously flooded treatment, the trend was similar to plant dry matter weight except
grain weight decreased in the 24 t ha⁻¹ of rice straw treatment. In the alternately flooded
and drained treatment, grain weight did not show any significant difference by increasing
rate of rice straw application. The alternately flooded and drained treatment significantly
increased grain weight compared with the continuously flooded treatment.

Grain yield from the 12.6 m² plots is shown in Figure 5.12. Whole plot grain yield from
the continuous flooded treatment increased with increasing rice straw application (12 to
24 t ha⁻¹). Grain yield in the alternately flooded and drained did not significantly increase
with increasing rates of organic matter or rice straw addition. The alternately flooded and
drained treatment resulted in greater grain yield than the continuously flooded treatment
at all levels of rice straw application.

The alternately flooded and drained treatment also influenced grain yield of the
ratoon crop (Figure 5.13). The ratoon grain yield with continuous flooding also increased
with increasing rate of rice straw. However, in the alternately flooded and drained
treatment the yield was not influenced by rice straw application rate. Even though it was
Figure 5.10 Effect of rice straw and water management treatments on dry matter weight; 
Figure 5.11 Effect of rice straw and water management treatments on grain weight from the sampling area (0.5 m$^2$); Grain F/D = alternately flooded and drained treatment, Grain F = continuously flooded treatment.
a second crop, grain yield of alternately flooded and drained was also greater than
the continuously flooded treatment. Grain yield of the ratoon crop was significant less
than the first crop for both continuously flooded and alternately flooded and drained
treatment. The highest grain yield of ratoon crop in alternately flooded and drained
treatment was 2.8 t ha$^{-1}$ while grain yield in the first crop was 8.2 t ha$^{-1}$. The treatment
with maximum grain yield in continuously flooded and drained in the second crop was
1.9 t ha$^{-1}$ while for the same treatment in the first crop the grain yield was 6.6 t ha$^{-1}$.

5.4 CONCLUSIONS AND SUGGESTIONS

The parameters we used as an indicator for appropriate time of draining were visual plant
growth stress of the rice plant. Draining immediately after the rice plant showed
symptoms can help prevent reduced stem numbers in rice straw at application rates (6,
12, or 24 t ha$^{-1}$). From the results of the pot experiment, we observed those plant injury or
stress symptoms at approximately 2 weeks after planting. If problem is expected then
better to schedule a drain before symptoms occur. No symptoms were observed in the
first two weeks because of two reasons. First, in the field, excess amount of circulated
water can dilute organic acid (or toxin) that might cause injuries to rice plant. Second,
under field conditions we would recommend “pinpoint” drainage approximately 5 days
after planting. This drainage could help reduce the amount of toxicant to levels that are
safe to the young rice seedling. However, injuries to rice were observed at the high straw
application rates (12 and 24 t ha$^{-1}$) in both water management treatments at fourth week
after planting. This suggests that draining was too late to prevent impact to rice growth.

From the results obtained from the experiment described above, we can draw the
following conclusions:
Figure 5.12 Effect of rice straw and water management practices on grain yield at 12 % moisture content of main crop (from whole plot); Yield F/D = alternately flooded and drained treatment, Yield F = continuously flooded treatment.
Figure 5.13 Effect of rice straw and water management treatments on grain yield (12 % moisture content) of ratoon crop (kg ha\(^{-1}\)); Alt. F/D = alternately flooded and drained treatment, Con. F = continuously flooded treatment.
1) Soil pH at high rice straw application rates fluctuated in the continuously flooded treatment. In alternately flooded and drained treatments, soil pH fluctuated less after draining. Draining for 10 days can help to maintain a uniform soil pH.

2) Average soil Eh in continuously flooded treatments was lower than the alternately flooded and drained treatments.

3) Plant growth, nutrient uptake and grain yield in the alternately flooded and drained treatments was significantly greater than in the continuously flooded treatments, especially nitrogen uptake, which is important to rice growth and productivity.

4) Added rice straw resulted in greater methane emission, which methane emission in the alternately flooded and drained treatments was significantly lower than in the continuously flooded treatments.

Although the continuously flooded treatment is not actually continuously flooded because of the “pinpoint” drain that is practiced in some farmers’ fields, the technique allows flooded rice soil to oxidize for a period of time during the growing season. This practice has the potential to increase grain yield and reduce methane emission at the same time. One important parameter that was not observed or measured in the field (but found in the pot experiment) was the decrease in plant number the first week following planting. In the field, “pinpoint” draining in both water treatments during the first week favors increased plant number. The “pinpoint” draining at the first week after planting might reduce the toxicity and the toxic compounds associated with organic matter decomposition under anaerobic conditions. Draining the field for a short period of time during the growing season can enhance rice growth, grain yield and reduce methane emission.
CHAPTER 6

EFFECT OF PLANT RESIDUE INCORPORATION ON RICE GERMINATION AND SEEDLING ESTABLISHMENT: GREENHOUSE STUDIES

6.1 INTRODUCTION

Data from the previous pot experiment indicated that high soil organic matter can severely impact rice growth and seedling development, especially the first 1-2 weeks following planting. Upon flooding or submerging, soil oxygen disappeared and soil redox potential (Eh) decreased, reaching stable values ranging from +200 to –300 mV depending on the soil type and other factors. The extent reducing conditions or low Eh depended on soil reductant capacity, which is governed by soil organic content. Rate of reduction or decrease in redox potential is influenced by initial soil oxygen concentration and the amount of alternate electron accepters such as Fe$^{2+}$, Mn$^{2+}$ and SO$_4^{2-}$ (De Datta, 1981). Extreme soil reduction can result in the generation of organic acids, ethylene, mercaptans, organic sulfides, and hydrogen sulfide (Ponnamperuma, 1978).

Decrease in Eh or pE ($pE = \frac{Eh}{0.059}$) and changes in secondary physicochemical properties brought about by soil submergence can have both positive and/or negative effects on rice growth (De Datta, 1981). Ponnamperuma (1978) suggested that the optimum soil Eh for rice growth was in the range of 10-120 mV (or pE 0.2-2.0) at a soil solution pH of 7.0.

In flooded soil, an increase in the supply of available soil nitrogen since mineralized nitrogen is generally greater. The supply of phosphorus, potassium, iron, manganese, molybdenum, and silicon in flooded soil can also increase as a result of soil reduction (De Datta, 1981). Negative impacts of flooding on rice growth include losses of nitrogen through denitrification; decrease in availability of sulfur, copper, and zinc; and
production of soil substances that either restrict nutrient uptake or is toxic to the rice plant (De Datta, 1981; Dobermann and Fairhurst, 2000; Cannell and Lynch, 1984).

Watanabe (1984) reported that anaerobic decomposition of organic matter in flooded rice soils leads to the accumulation of volatile fatty acids (VFA) such as acetic, propionic, and butyric, and subsequent VFA decreases associated to the increasing of CH$_4$ and sulfide. He also mentioned that type of organic matter and type and volume of the oxidizing agent are important factors affecting anaerobic decomposition. Additional factors such as temperature, percolation, soil properties, and plant species are also important factors affecting decomposition (Watanabe, 1984). Mitsui et al. (1959 quoted in Watanabe, 1984) claimed that the growth-retarding action of organic matter amendments to rice was worsening in cool soil temperature because at lower soil temperature more VFA accumulated (Cho and Ponnamperuma, 1971).

Root injury of rice seedlings followed by stunted growth has been observed in waterlogged soils containing high levels of readily decomposable organic matter (Cannell and Lynch, 1984). Gao et al. (2003 and 2004) and Tanji et al. (2002) reported that straw addition to paddies could promote reducing conditions that could increase sulfide levels resulting in plant toxicity. Sulfide toxicity has been documented in many studies and is characterized by blackened roots, retarded plant growth, reduced plant density, and even death in severe cases (Cannell and Lynch, 1984; Gao et al, 2004). In addition, the extracts from shoots of grass species decomposing under anaerobic condition have been found to be toxic to other grasses (Gussin and Lynch, 1981). As has been observed with rice, the phytotoxicity will diminish with time. The extracts from residues of different plant species differed in phytotoxicity. For example, extracts from (Red Fescue) Festuca
rubra, (Meadow Foxtail) Alopecurus pratensis, and (Bentgrass) Agrostis stolonifera decomposing under anaerobic condition are some of the most toxic (Cannell and Lynch, 1984).

This following experiment was conducted in order to examine the effects of rate and source of soil plant residue addition on germination and seedling development of several rice varieties. The sources of plant residue were chopped and ground rice straw and Alligator weed (Alternanthera philoxeroides).

6.2 MATERIALS AND METHODS

6.2.1 Germination Studies

Crowley silt loam (Typic Albaqualf) was collected from the Crowley Rice Research Station. 140 g air-dried soil was placed into 15 x 15 x 7.5 cm Styrofoam sandwich box. A 4 x 3 x 5 factorial experiment was arranged in a split-split plot design with four rice varieties (Cocodrie, XL8, Wells, and Pirogue) as main plot treatments, three sources of plant residue (chopped rice straw, ground rice straw, and alligator weed) as sub plot treatments, and five rates of plant residue application (0, 4, 8, 16, and 32 t ha$^{-1}$) as sub-sub plot treatments. The experimental design included four replications. The soil samples were mixed thoroughly with either 0.32, 0.64, 1.28, and 2.56 g (equivalent to 4, 8, 16, and 32 t ha$^{-1}$) of chopped rice straw (1-2 cm-pieces), ground rice straw passed (through 0.5 mm screen), and alligator weed (1-2 cm section). Distilled water (120 mL) was added to each treatment and checked daily to maintain flooded conditions. A parallel set of soils mixed with organic matter containing two platinum electrodes was used for measuring changes in soil redox (Eh) condition. Soil treatment without a pH electrode was planted with pre-germinated seeds. Pre-germinated seeds were prepared by soaking the seed in
water for 24 hours and then drained for 24 hours. The pre-germinated seeds were transferred into the Styrofoam box containing the soil/plant residue treatment at a rate of 25 seeds per treatment. The seeds were placed approximately two cm apart. The number of seed germinated was recorded after seven days. Soil pH and redox potential were recorded twice per day.

Redox potential in the treatment was measured using platinum electrodes and a calomel half-cell. Two replicate platinum electrodes were inserted into the soil samples and allowed to equilibrate for 24 hours before recording Eh. The pH was measured using a combination glass-reference electrode.

6.2.2 Statistical Analysis

The data were statistically analyzed using IRRISTAT software (IRRI, 1992). If any results from ANOVA analysis showed significant differences, then mean comparisons were obtained with Duncan’s Multiple Range Test (DMRT).

6.3 Results and Discussion

6.3.1 Seed Germination

Germination rate of each rice variety was determined prior to initiation of the experiment. The results are shown in Table 6.1. The Pirogue rice variety had an average germination rate of 78% (68 – 85%) less than the other varieties. The Wells variety had maximum germination of 96% (94-99%). The Cocodrie and XL8 varieties had germination rates at 92 and 90%, respectively.

Germination rate after the first week as affected by plant residue treatments (rice straw and alligator weed) is shown in Table 6.2. Cocodrie, XL8, and Wells did not show a significant difference in rate of germination; Pirogue had a lower germination rate
compared with the other varieties. The low germination rate of Pirogue was associated with the overall low germination rate of this variety compared with the others.

Added ground rice straw had no affect on germination of Cocodrie, XL8, and Pirogue. The germination rate of Wells was reduced in soil where organic matter was applied at the rate of 32 t ha\(^{-1}\). Application of chopped rice straw had no significant effect (p > 0.05) on germination of XL8 (87% germination in the treatment without ground rice straw and 81% at 32 t ha\(^{-1}\)) and Pirogue (73% and 59% at 0 and 32 t ha\(^{-1}\), respectively) and Cocodrie (85% and 72% at 0 and 32 t ha\(^{-1}\), respectively). Germination of the Wells cultivar had a significantly lower (p < 0.05) germination rate (87% and 71% in 0 and 32 t ha\(^{-1}\), respectively).

Table 6.1 Germination rate of rice varieties (%).

<table>
<thead>
<tr>
<th>Variety Rep</th>
<th>Cocodrie (%)</th>
<th>XL8 (%)</th>
<th>Wells (%)</th>
<th>Pirogue (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>89</td>
<td>91</td>
<td>96</td>
<td>80</td>
</tr>
<tr>
<td>II</td>
<td>93</td>
<td>91</td>
<td>94</td>
<td>68</td>
</tr>
<tr>
<td>III</td>
<td>94</td>
<td>87</td>
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<td>85</td>
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<tr>
<td>Average</td>
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<td>90</td>
<td>96</td>
<td>78</td>
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<tr>
<td>SD (%)</td>
<td>2.7</td>
<td>2.3</td>
<td>2.5</td>
<td>8.7</td>
</tr>
</tbody>
</table>
Table 6.2 Effect of sources of plant residue and rates on germination of rice varieties (%)

<table>
<thead>
<tr>
<th>Sources of plant residue</th>
<th>Rate (t/ha)</th>
<th>Varieties</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cocodrie</td>
<td>XL 8</td>
<td>Wells</td>
<td>Pirogue</td>
</tr>
<tr>
<td>Ground Rice Straw</td>
<td>0</td>
<td>85 a</td>
<td>87 a</td>
<td>86 a</td>
<td>73 a</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>84 a</td>
<td>84 ab</td>
<td>81 ab</td>
<td>74 a</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>79 a</td>
<td>74 b</td>
<td>82 ab</td>
<td>68 a</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>82 a</td>
<td>80 ab</td>
<td>87 a</td>
<td>59 a</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>72 a</td>
<td>81 ab</td>
<td>71 b</td>
<td>59 a</td>
</tr>
<tr>
<td>Chopped Rice Straw</td>
<td>0</td>
<td>80 a</td>
<td>80 a</td>
<td>83 a</td>
<td>72 a</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>74 a</td>
<td>81 a</td>
<td>80 a</td>
<td>70 a</td>
</tr>
<tr>
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<td>76 a</td>
<td>88 a</td>
<td>73 ab</td>
<td>71 a</td>
</tr>
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<td>16</td>
<td>58 b</td>
<td>82 a</td>
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<tr>
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<td>32</td>
<td>56 b</td>
<td>79 a</td>
<td>64 b</td>
<td>62 a</td>
</tr>
<tr>
<td>Alligator Weed</td>
<td>0</td>
<td>83 a</td>
<td>82 a</td>
<td>84 a</td>
<td>76 a</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>77 ab</td>
<td>84 a</td>
<td>77 a</td>
<td>76 a</td>
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<td></td>
<td>8</td>
<td>67 b</td>
<td>80 a</td>
<td>55 b</td>
<td>59 b</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>41 c</td>
<td>59 b</td>
<td>31 c</td>
<td>23 c</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>3 d</td>
<td>9 c</td>
<td>3 d</td>
<td>2 d</td>
</tr>
</tbody>
</table>

CV (sources)  | 52 ** | 45 ** | 66 ** | 49 ** |
CV (rates)     | 59 ** | 39 ** | 43 ** | 72 ** |

In a column under each source of plant residue, means followed by a common letter are not significantly different at the 5% level by DMRT.
In contrast to rice straw, alligator weed as the organic matter source added to the soil showed significant germination inhibition for all varieties tested. The germination of Cocodrie, Wells and Pirogue was decreased when the rate of alligator weed reached 8 t ha\(^{-1}\), while the germination of XL8 was decreased at an application rate of 16 t ha\(^{-1}\).

Regression coefficients (R Square) between sources of organic matter and germination of each variety are showed in Table 6.3. Alligator weed addition was negative correlated to germination of all varieties tested (-0.89** for Cocodrie, and -0.86** for XL8, Wells and Pirogue).

6.3.2 Soil Redox and pH

Soil redox potential in treatments without plant residue amendment varied from +200 mV to +420 mV. The higher application rate of chopped rice straw displayed lower redox potential compared with the lower rates of rice straw application (Figure 6.1 a).

Redox potential in soil treatments receiving chopped rice straw at the rates of 16 and 32 t ha\(^{-1}\) was significantly lower than soil redox potential in treatment rates of 4 and 8 t ha\(^{-1}\). Soil redox potential decreased from +250 mV to 0 mV at 5 days after flooding in the treatment receiving 32 t ha\(^{-1}\) of chopped rice straw treatment. At 8 t ha\(^{-1}\) of added chopped rice straw application, soil redox potential was less than 0 mV, 12 days following flooding. At 4 t ha\(^{-1}\) the lowest measured redox potential over the flooding period was approximately 0 mV.

In the soil treatment receiving ground rice straw, initial soil redox potential varied from +190 mV to +390 mV for 8 and 32 t ha\(^{-1}\) plant residue addition, respectively (Figure 6.1 b). Overall soil redox potential varied, depending on the rate of added ground rice straw among treatments. Soil redox potential dropped from +190 mV to 0 mV 3 days
Table 6.3 Regression coefficient (R squares) between germination rates (%) and sources of plant residue.

<table>
<thead>
<tr>
<th>Rice Varieties</th>
<th>Source of Plant Residue</th>
<th>Ground Rice Straw</th>
<th>Chopped Rice Straw</th>
<th>Alligator Weed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cocodrie</td>
<td>-0.49**</td>
<td>-0.30*</td>
<td>-0.89**</td>
<td></td>
</tr>
<tr>
<td>XL8</td>
<td>0.00ns</td>
<td>0.00ns</td>
<td>-0.86**</td>
<td></td>
</tr>
<tr>
<td>Wells</td>
<td>-0.26*</td>
<td>-0.38*</td>
<td>-0.86**</td>
<td></td>
</tr>
<tr>
<td>Pirogue</td>
<td>-0.14ns</td>
<td>-0.12ns</td>
<td>-0.86**</td>
<td></td>
</tr>
</tbody>
</table>

ns = non significant different
* = significant different at 5% level
** = significant different at 1% level
following flooding reaching -380 mV, 14 days after flooding for the highest rate of
ground rice straw addition (32 t ha\(^{-1}\)). Soil redox potential in treatments receiving 16 and
32 t ha\(^{-1}\) of ground rice straw had the same Eh pattern after 5 days of flooding. After 18
days, soil redox potential (Eh) of all the treatments receiving ground rice straw was near -
300 mV.

Soil redox potential of alligator weed treatments decreased dramatically during
the first 3 days following flooding (Figure 6.1 c). Soil Eh of 32 t ha\(^{-1}\) treatment decreased
from +180 mV to -220 mV after only 3 days of flooding. Alligator weed at the
application rate of 16 t ha\(^{-1}\) decreased soil redox potential from +300 mV to -250 mV
after 3 days of flooding. After 4 days of flooding, the redox potential of soil treatments
with alligator weed at 16 and 32 t ha\(^{-1}\) was steady with little further decrease. The higher
rates of alligator weed resulted in statistically lower soil redox potential compared with
the treatment without plant residue. However, there was no significant difference in soil
redox between the 16 t ha\(^{-1}\) and 32 t ha\(^{-1}\) treatments.

The low redox potential of soil treatments receiving added alligator weed as an
organic matter source could have adverse effects on rice germination. The rapid decrease
in soil redox potential would create extremely reduced soil conditions, depleting soil
oxygen. Such conditions would not be favorable for rice seedling development. In the
treatments receiving ground rice straw amendments, the soil redox potential decreased
more rapidly compared with chopped rice straw application. However, the decrease in
redox potential for both rice straw amendments was not as rapid as that observed for the
alligator weed treatment. Soil redox potential of 32 t ha\(^{-1}\) of ground rice straw dropped
from 200 mV to -200 mV after 5 days of flooding. The slower decrease in redox potential
Figure 6.1 Effect of sources and rates of plant residue on soil redox potential at different time of incubation, a) = chopped rice straw, b) = ground rice straw, and c) alligator weed.
from rice straw would allow sufficient time for rice seedling development and establishment when compared with the alligator weed amendments.

Alligator weed addition had a greater effect on soil pH when compared with rice straw amendments (Figure 6.2 a, b, c). The higher rate of chopped rice straw application resulted in an increased soil pH. Overall soil pH for the different rates of chopped rice straw varied between 7.6 and 8.2 and increased slightly during the first six to eight days of flooding. After this period the soil pH remained constant. In the grounded rice straw treatment, the change in soil pH was similar to the chopped rice straw treatment (Figure 6.2 b). For the alligator weed treatment, soil pH ranged from 6.5-7.8 for alligator weed addition of 4 and 8 t ha$^{-1}$ with a slight increase over time (Figure 6.2 c). At the 16 and 32 t ha$^{-1}$ alligator weed amendments, soil pH rapidly dropped from 6.7 to 5.6 and 6.7 to 5.0, respectively, after only one day of flooding. Following this rapid decrease, soil pH of both treatments increased slightly over time. However, the soil pH of the 32 t ha$^{-1}$ treatment increased at a slower rate compared with other treatment rates. At the end of our monitoring period (18 days), soil pH of all treatments ranged from 7.0-7.5 and the lowest pH was found at the highest rate (32 t ha$^{-1}$) of alligator weed application.

6.4 CONCLUSIONS AND SUGGESTIONS

This study has shown that amount and plant residue sources can influence germination of rice varieties. The organic matter also influenced soil redox potential and pH. Alligator weed amendment severely impacted rice seedling development and was negatively correlated with seed germination for all varieties studied (-0.86** for XL8, Wells, and Pirogue varieties and -0.89** for Cocodrie variety). The application of alligator weed to
Figure 6.2 Effect of sources and rates of plant residue on soil pH at different time of incubation, a) chopped rice straw, b) ground rice straw, and c) alligator weed.
soil resulted in a rapid decrease in soil redox potential and soil pH compared with treatments receiving rice straw application.

The highest plant residue application rate (32 t ha\(^{-1}\)) (chopped rice straw, ground rice straw, and alligator weed) resulted in decreased germination of rice seeds and decreased soil redox potential when compared with the lower rates of application. At 16 and 32 t ha\(^{-1}\) of both ground and chopped rice straw applications tended to increase soil pH, while the same rates of alligator weed resulted in lower soil pH.

Rice varieties had different rates of germination and growth depending on sources and rates of plant residue addition. Cocodrie and Wells varieties were more susceptible to the toxicity effect of plant residue compared with XL8 and Pirogue varieties. All sources of organic matter suppressed germination of Cocodrie and Wells at higher rates. Alligator weed addition suppressed germination of all varieties.

These results suggest at least two management options to plant rice in soils with a high content of plant residue. One management practice would be to avoid planting rice in soils with high plant residue which results in low soil redox potentials, which would restrict rice seedling development. If these conditions exist, farmers should delay planting approximately 5-10 days after flooding or drain the field to increased soil redox potential and reflooding before planting. A second option would be to choose a rice variety that is more tolerant to the adverse soil conditions created by plant residue. Varieties such as XL8 and Pirogue could more likely become established under such condition compared with Cocodrie and Wells. Also, farmers should take extra care in planting rice when alligator weed has been incorporated into the soil seedbed.
CHAPTER 7

SUMMARY AND RECOMMENDATIONS

7.1 EFFECT OF RICE STRAW AND WATER MANAGEMENT PRACTICES ON SOIL pH AND REDOX CHEMISTRY IN FLOODED RICE SOIL

Soil pH decreased slightly at an increased rate of rice straw application in both water management treatments. Soil pH in the continuously flooded treatment fluctuated during the first week after planting. Soil pH in both water management treatments was fairly constant from the third week until harvest and was not affected by the rate of rice straw application. However, soil pH was not significantly different (p >0.05) in either rice straw application or water management treatments for both pot or field experiments.

Soil redox potential in the pot experiment correlated with rice straw rates. The lowest soil redox potential (-278 and -280 mV) was measured in the highest rice straw application (16 t ha\(^{-1}\)) in the alternately flooded and drained and the continuously flooded water management treatments, respectively. The expected high redox potential of the alternately flooded and drained treatment was not observed in the experiment. This was attributed to the draining of surface water in the pots in this experiment. Even though the soil surface in the pots was dry, the moisture in the soil at the depth of 10-15 cm remained saturated. However, in the field experiment the high redox potential was observed immediately after draining the field and remained high during the drainage period in the alternately flooded and drained treatment.

7.2 EFFECT OF RICE STRAW AND WATER MANAGEMENT ON METHANE EMISSION FROM FLOODED RICE SOIL

Methane emission from flooded rice soil was significant correlated with organic matter level. Higher rates of rice straw in soil enhanced methane emission more than the
lower rates of rice straw in both water management treatments. In the pot experiment, methane emission in the alternately flooded and drained treatment was significantly (p <0.01) less than that of the continuously flooded treatment, especially with 16 t ha\(^{-1}\) rice straw application. Methane emission was 668, and 1400 kg·ha\(^{-1}\) season\(^{-1}\), respectively. The result of the field experiment was similar to the pot experiment, which the treatment receiving the highest rice straw (24 t ha\(^{-1}\)) had significantly greater (p <0.01) methane emission than with the lower rice straw rates. Total methane emission of the highest rice straw rate (24 t ha\(^{-1}\)) in the continuously flooded and drained treatment and in the continuously flooded treatment was 3,260 and 7,350 kg·ha season\(^{-1}\), respectively. These results indicated that draining rice fields for some period of time could be a feasible method to reduce methane emission from wetland rice ecosystem.

7.3 Effect of Rice Straw and Water Management Practices on Rice Growth and Grain Yield

This study has shown amount and sources of plant residue can influence germination of rice. Plant residue also influenced soil redox potential, and pH. Alligator weed amendment severely impacted rice seedling development and was negatively correlated with seed germination for all varieties studied (-0.86** for XL8, Wells, and Pirogue varieties and -0.89** for Cocodrie variety). The application of alligator weed to soil resulted in a rapid decrease in soil redox potential and soil pH compared with treatments receiving rice straw application.

The highest rate of plant residue application (32 t ha\(^{-1}\)) (chopped rice straw, ground rice straw, and alligator weed) resulted in decreased germination of rice seeds and soil redox potential compared with lower rates of application. In the treatments receiving 16 and 32 t ha\(^{-1}\) of both ground and chopped rice straw tended to increase soil pH, while these rates of alligator weed resulted in lower soil pH.
Rice varieties had different abilities to germinate and grow depending on sources and rates of plant residue addition. Cocodrie and Wells varieties were more susceptible to toxicity effects of plant residue compared with XL8 and Pirogue varieties. All sources of plant residue suppressed germination of Cocodrie and Wells at higher rates. Alligator weed addition suppressed germination of all varieties.

Application of rice straw at 8 t ha\(^{-1}\) and higher in the pot experiment resulted in prolonged maturity of rice, approximately 1-2 weeks in both water management practices. The result was the same for the pot and the field experiment. The treatments receiving 12 and 24 t ha\(^{-1}\) of rice straw incorporation resulted in delayed heading. Rice grain yield in the pot experiment was significantly greater (p < 0.05) for the higher rice straw application rate in both water management treatments. However, rice grain yield in the alternately flooded and drained treatment of the higher rice straw rate was not significantly different compared with the lower rice straw rates in the field experiment. In addition, the ratio between grain weight and stem weight in alternately flooded and drained treatment was significantly greater (p < 0.05) than the continuously flooded treatment, especially in the treatment receiving a higher rate of rice straw. This result indicated that the higher rate of rice straw enhanced more vegetative growth (stem) than reproductive growth (grain).

7.4 WATER MANAGEMENT PRACTICES IN FLOODED RICE SOIL

Although the continuously flooded treatment is not actual continuously flooded because of the “pinpoint” drain practiced in some farmers’ fields, the technique allows flooded rice soil to oxidize for a period of time during the growing season. This practice has the potential to increase grain yield and reduce methane emission simultaneously. One important parameter that was not observed or measured in the field (but found in the pot
experiment) was the decrease in plant number the first week following planting. In the field, “pinpoint” drain in both water treatments during the first week favors increase plant number. The “pinpoint” drain at the first week after planting might reduce the toxicity and the toxic compounds associated with plant residue decomposition under anaerobic condition. Draining the field for a short period of time during growing season can enhance rice growth, grain yield and reduce methane emission.

The alternating flooded and drained cycles in the rice field for some period of time significantly increased plant growth in both the pot and field experiment. This is attributed to the reduction of toxic elements and some toxic intermediate organic acids (that occurred during decomposition of organic materials), and increases in the availability of some nutrients resulting from the mineralization of organic nitrogen.

7.5 RECOMMENDATIONS

These results suggest at least two management options to plant rice in soils with a high content of plant residue. One management practice would be to avoid planting rice in soils with high plant residue which results in low soil redox potentials, which would restrict rice seedling development. If these conditions exist, farmers should delay planting approximately 5-10 days after flooding or draining the field to increase soil redox potential and reduced toxics from the decomposition process of plant residue, and then reflooding before planting. A second option would be to choose a rice variety that is more tolerant to the adverse soil conditions created by soil plant residue. Varieties such as XL8 and Pirogue could be more likely to become established under such condition as compared to Cocodrie and Wells. Also farmer should take extra care in initially planting in field when alligator weed has been incorporated into the soil seedbed.
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APPENDIX A: GLOBAL POSITION SYSTEM (GPS) OF THREE COMMERCIAL FARMS.

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<th>Longitude</th>
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APPENDIX B: METHANE EMISSION (KG HA\(^{-1}\) D\(^{-1}\)) FROM POT EXPERIMENT.

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APPENDIX C: METHANE EMISSION (KG HA\(^{-1}\) D\(^{-1}\)) FROM FIELD EXPERIMENT, CROWLEY, 2003.

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<th>25-Apr</th>
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<th>19-May</th>
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<th>5-Jun</th>
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<th>4-Jul</th>
<th>24-Jul</th>
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APPENDIX D: GRAIN YIELD (T HA\(^{-1}\)) OF THE FIRST CROP FROM FIELD EXPERIMENT, CROWLEY 2003.

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<tr>
<td>and drained</td>
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APPENDIX E: GRAIN YIELD (T HA\(^{-1}\)) OF RATOOON CROP FROM FIELD EXPERIMENT, CROWLEY, 2003.

<table>
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VITA

The author was born in Thailand in 1961. He received his Bachelor of Science in 1983 and Master of Science in 1986 from the faculty of Agriculture, Khon Kaen University, Thailand, specializing in soil science both as undergraduate and graduate majors.

He worked for The International Rice Research Institute (IRRI) as a Researcher on “Site Specific Nutrient Management in Irrigated Rice Ecosystems” from 1987 to 2001. He started his doctoral program in the Department of Agronomy and Environmental Management in 2001, under the supervision of Dr. Ronald D. DeLaune. He majored in agronomy with emphasis on wetland soils management, and minored in environmental toxicology. Meanwhile, he is working for Master of Science degree in the Department of Environmental Studies, majoring in environmental planning and management.

He is a member of American Society of Agronomy (ASA), Soil Science Society of America (SSSA), Society of Wetland Scientists (SWS), and Louisiana Association of Agronomists (LAA). He has been serving as an Instructor in the Department of Agronomy and Environmental Management since June 2004.