EFFECT OF WATER-SAVING IRRIGATION PRACTICES ON FATE OF INORGANIC NITROGEN, PLANT GROWTH AND YIELD IN RICE

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I do hereby declare that the thesis with the above mentioned title presented herein for the degree of Doctor of Agricultural Sciences is the result of my own experiments. All the references to other's work as source of information are fully acknowledged.

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ABBREVIATIONS

ADB	Asian development bank
ANOVA	Analysis of variance
AWD	Alternate wetting and drying
CEC	Cation exchange capacity
DAH	Days after heading
DAT	Days after transplanting
DBH	Days before heading
DF	Drying and re-flooded
EMSD	Early mid-season drainage
EMSD10	Early mid-season drainage 10 days
EMSD20	Early mid-season drainage 20 days
EMT	Early mid-tillering
ET	Early tilleing
FAO	Food and agriculture organization
H	Heading
IRRI	International rice research institute
LPS	Long performing sigmoid
LSD	Latin square design

MEXT	Ministry of education, culture, sports, science and technology
MSD	Mid-season drainage
MT	Maximum tillering
MT	Mid-tillering
N	Nitrogen
NS	Non- significant
PI	Panicle initiation
RCD	Randomized completer design
SMC	Saturated moisture content
SRI	System of rice intensification
SWD	Shallow water depth
USDA	United States Department of Agriculture
WPS	World population statistics

CHAPTER 1

GENERAL INTRODUCITON

1.1 World population and food production

The population of the world grew from about 300 million at the beginning of the Christian era to half billion in 1650 to one billion in 1800, to two billion in 1927, to three billion in 1960, to four billion in 1974, and to five billion in 1987 (FAO, 2012). This trend indicates that world population increases exponentially. The world population is projected to grow eight billion in 2023, nine in 2050, and ten around 2100 (FAO, 2012).

The world food production (maize, wheat, rice, beans, oil crops, roots and tubers) grew to1180 million metric ton (Mt) in 1965, to 1402 million Mt in 1975, to 1624 million Mt in 1985, to 1846 million Mt in 1995, to 2068 million Mt in 2005 (FAO, 2012). The world food production is projected to grow 3009 million Mt by 2050 (FAO, 2012). This trend indicates that world food production increases linearly.

However, an average rate of the world agricultural production of annual growth in per capita production has been in a downward trend for some time now, falling from 3.7% in 1960, 2.5% in 1970, 1.4% in 1980, and 1.1% in 2001. Furthermore, the average rates of annual growth in per capita production is supposed to be declined to grow 0.54% in 2020 and 0.25% in 2050 (FAO, 2012).

The world population and demand of food production was increased from now to earlier several decades. The annual food production was need to increased 37 percent in 1961/1963 for 3 billion people, 100 percent in 2005/2007 for 6 billion people. The annual world food production would need to increase 138 percent in 2030 for 8 billion people and 160 percent in 2050 for 9 billion people. Thus, annual world food production would need to increase by approximately 60 percent from 2005/2007 to 2050 (FAO, 2012). Therefore, the world needs more food for meet up their demand.

Overall demand for agricultural products (including food, feed, fiber and oil crops) is expected to increase agricultural products 1.1 percent year from 2005/7 to 2050. Despite lower food growth rates, the absolute quantities of food necessary to feed the world in 2050 are substantial. Assuming no change in population growth, food consumption patterns and food management, the following production increased must take place by 2050. Cereals production must increase by 940 million Mt to reach 3 billion Mt. Meat production must increase by 196 million Mt to reach 455 million Mt; oil crops (oil-palm, soybean, sunflower and rapeseed) must increase by 133 million Mt to reach 282 million Mt, and roots and tubers (cassava, potato, sweet potato and yam) must increase by 927 million Mt (Tillmen *et al.*, 2011).

Global demand for water has risen sharply over the last century. Total annul water withdrawal (for agricultural, industries and municipalities) rose from less than 600 km^3 $year^{-1}$ at the beginning of the twentieth century, to 1350 km^3 $year^{-1}$ in the middle of the century and more than 3800 km^3 $year^{-1}$ by the beginning of the twenty-first (FAO, 2012). Today irrigated agriculture account for about 70 percent of freshwater withdrawals throughout the world. Irrigation has been crucial for gains in food production. For growing irrigated rice, 2000-3000 liters of water required to produce 1 kg of rice (IRRI, 2009). An increasing water shortage is apparent in many nations due to global surface air temperature increased (FAO, 2009). In the past 100 yr (1906-2005), the global surface air temperature increased by 0.74^0C, ranging from 0.56 to 0.92^0C (IPCC, 2007a) due to green house gases effect. By the end of 21^{st} century, the global air surface temperature will continue to increase by 1.8 to 4^0C (IPCC 2007a). At the global scale, precipitation tended to increase in the high latitude regions of the Northern Hemisphere while the precipitation decreases in the semi-tropical regions over the past several decades (IPCC 2007a). The change of climate and its variability influence many aspects of the society, of which, the concerns on the impact of climate change on water security and agricultural production have been growing. Wang *et al.* (2009) found that under climate changes, increase of water scarcity will result in the decline of irrigated areas, which will further influence the agricultural production. Decreasing water availability for agriculture threatens the productivity of agricultural crops and ways must be sought to save water and increase the water productivity of agricultural crops (Guerra *et al.*, 1998; Belder *et al.*, 2004).

1.2 Present population and food production situation in Asia

Asia is the world's largest and most populous continent with approximately 4.3 billion people; it hosts 60% of the world's current human population (FAO, 2012). Asia has a high growth rate in the modern era and has increased fourfold during the last 100 years and will add about 1 billion people by 2050 (WPS, 2012). In Asia, the total cereal (rice, wheat, milled rice, maize and coarse grain), roots and tubers, beans and oil crops production increased, from the 1960s through to the 1980s, is likely to continue up to now (FAO, 2012).

Rice (*Oryza sativa* L.) is one of the most important crops and the foremost staple food in Asia, providing 35 to 60% of the dietary calories consumed by more than 3 billion people (Fageria, 2003). Indeed, it is anticipated that rice production will need to increase 60% by 2025 in order to sustain those who need it for sustenance (Fageria, 2007). However, climate change, especially access to water, soil erosion and other problems threaten rice yields. A study by the International Water Management Institute suggested that by 2020, one third of Asia could face water shortage (IRRI, 2010).

Ninety percent of the world's rice is produced and consumed in Asia (IRRI, 2005). Rice cultivated area in Asia is about 139 million ha (USDA, 2009). About 56% of the rice supply comes from 81 million ha of irrigated land (FAO, 2013). Most of the expansion of irrigated land is achieved by converting land in use in rain-fed agriculture into irrigated land. It assumes that losses of existing irrigated land due to water shortages or degradation because of salinization and water logging, irrigated land will be compensated for through rehabilitation or substitution by new areas for those lost (FAO, 2012).Therefore, the total harvested area of irrigated rice was changeable over past decades.

From 1961 to 1990, the harvested rice area in Asia had increased by about 30%, due to a combination of the expansion in cultivated area and crop intensification. The expansion of crop intensification due to crop production can be increased by increasing the extents of agricultural land, which as evident from the above becomes an impossible task. The other alternative is to bring additional land under cultivation by expanding into marginal lands in different countries, but these have been almost exhausted and even with heavy investment may remain marginal. Hence, of the available options increase in intensity of cultivation and in yields per unit areas are the only available options to meet future food needs to feed an ever increasing population (IRRI, 2009).

Inorganic fertilizers have led to a rapid increase in rice yield during 1961-1990 (from about 1.87 Mt ha^{-1} in 1961 to about 3.61 Mt ha^{-1} in 1990) (FAO, 2009). As a result of the increases in both harvested area and yield, rice production in Asia has nearly tripled during 1961 to 1997 (from 198.75 million ton of paddies in 1961 to about 522.84 million ton in 1997) (FAO, 2009). The growth rate in rice yield, however, has been considerably slowed down since 1990 (FAO, 2009).

In 2005, about 56 percent of the total harvested areas come from irrigated ecologies, 31.4% from rain-fed lowland, 7.7 % from upland and 4.9% from other ecologies (FAO, 2012). The area equipped for irrigation has been continuously expanding although more recently this expansion has slowed down. The projections of irrigation presented below reflect necessarily scattered information on existing irrigation expansion plans in the different countries, potentials for expansions (including water availability) and need to increase crop production (FAO, 2012). There are several constraints to sustainable rice production in Asia. Following are the major ones: i) water availability in rice ecosystem is the primary factor determining the success of the rice crop. Water resources are being increasingly used by the industry and household sectors, ii) rapid urbanization and industrialization have encouraged farmers to exploit marginal lands (Brekke *et al*., 2009). For expansion irrigated rice areas, there are some main technical opportunities: i) improving water availability or water use by water-saving irrigation techniques, ii) high yielding variety with resistance to pests and diseases, low sterility and acceptable grain quality iii) for guiding the application of Nitrogen (N) fertilizer by Integrated Pest Management, Integrated Plant Nutrition Management, the Leaf Colour Chart, iv) acid soils, tidal lands, forest lands, etc. have been reclaimed and put under cultivation (Geerts and Raes, 2009).

From 1970 to 2007, the cultivated land use was increased in Asia only by 3% where cereal production increased by 137%. Today, 73% of the water consumed globally for agricultural in used in Asia (ADB, 2012). Asian irrigation is now at a crossroads. Increasing populations, changing diets, growing cities, and expanding energy and industrial production each demand a greater share of available water resources.

Rain-fed rice is grown on approximately 59 million ha, 31.4% of the total rice area (Maclean *et al*., 2010). Averaged yield of rain-fed rice is low at 2.1 ton ha^{-1}, and productivity is generally constrained by uncertain water supply, low soil fertility, pest (insects, pathogens, weeds) infestation (Wade *et al*., 1999a) and poverty (Dawe, 2007).

Upland make up about 50 million ha of land (included maize and other upland crops) with over 100 million people dependent upon them (Pandey and Khiem, 2005). The area under uplands rice is reported to be 15 million ha. In Asia, most of the tropical and sub-tropical countries have higher precipitation and thus enough in irrigated lowland rice is required during mono rice culture but 2 to 3 rice culture required more water than mono rice culture per year.

In addition, irregular rainfall pattern also influenced the availability of irrigation water under rain-fed rice. During rain-fed rice culture, rainfall is a vital factor for rice growing to harvesting. If there is a deficit rainfall occurred during rice growing period, the yield level affected directly. For minimizing that adverse effect during rain-fed rice cultivation, irrigation can improve the situation and also minimize the yield loss risk. Similarly, if irrigated facilities can be used by wheat, beans, roots and tubers, oil crops etc., yield level will be increased. Therefore, irrigation facilities can alters the rain-fed ecologies from the decreasing yield risk during crop growing periods and consumption of irrigated water should be reduced.

1.3 Pollution problem in rice production

Irrigated lowland rice production systems are known to be significant sources of methane (CH_4) and nitrous oxide (N_2O), which are two important trace gases contributing to an observed increase of approximately 0.6–0.7 ^0C in global surface temperature during the last century (Trenberth *et al.*, 2007). Traditional continuous flooding water management results in a large amount of CH_4 emission from paddy field (Yagi *et al.*, 1996; Setyanto *et al.*, 2000). Methane emissions decline during drainage period to near zero and increase after re-flooding (Bronson *et al.*, 1997). Water-saving irrigation practice is one of the most important factors influencing CH_4 emission from paddy field (Khalil and Shearer, 2006). CH_4 formation through methanogenic activity occurs under strictly anaerobic conditions from paddy field (Rothfuss and Conrad, 1993).

It is not an important source of atmospheric N_2O for that as the intermediary product of denitrification. N_2O would be further reduced to nitrogen (N_2) under the strongly anaerobic conditions of paddy soils (Granli and Backman, 1994). It is generally recognized that, anaerobic–aerobic cycling can promotes N_2O emission from paddy field (Huang *et al.*, 2007).

Some of the water-saving techniques, such as mid-season drainage (MSD) and intermittent irrigation etc. have the great potential against pollution problem. The water-saving techniques will cause anaerobic and aerobic cycling, are considered to be options for reducing CH_4 emission from paddy field (Guo and Zhou, 2007).

Changing water management appears to be the most promising mitigation option for CH_4 and is particularly suited to reducing CH_4 emissions in irrigated rice production. MSD and intermittent irrigation reduce methane emissions by over 40 percent. Shallow flooding provides additional benefits, including water conservation and increased yields (Yan *et al.*, 2005)

1.4 N in paddy field

N is one of the essential macro elements for growth of rice and yield in almost all environments (Yoshida, 1981). N is in most cases added as inorganic fertilizer, although organic fertilizers are also used sometimes to enhance N availability. N is a constituent in all nucleic acids and proteins that allow plants to grow and survive. Since N is essential in these abundant molecules, most plant tissues invariably require minimum amounts of N to grow. It is, however, one of the most expensive inputs and if used improperly.

In continuous flooding fields, N is almost solely available as ammonium (NH_4) and N losses are predominantly through NH_3 volatilization (Vlek and Craswell, 1981). Similarly, in non-flooding field condition, which allowing the soil to become (temporarily) aerobic will enhance nitrification. If the nitrate (NO_3) is not taken up by rice plant, it is prone to denitrification losses (Reddy and Patrick, 1976; Eriksen *et al.*, 1985) or leaching in more permeable soils (Keeney and Sahrawat, 1986). From a plant nutritional point of view, a mixture of NH_4 and NO_3 is better for N uptake and growth of the rice plant than the sole availability of NH_4 or NO_3 (Ta *et al.*, 1981; Qian *et al.*, 2004). Therefore, water-saving regimes which allowing the soil to become aerobic temporarily will enhance nitrification may lead to higher N uptake and biomass growth, but may also lead to higher N losses and a reduced biomass growth if availability of NO_3 is not taken up by rice plant, it is prone to denitrification losses.

It is commonly found that only 30 to 50% of fertilizer N is taken by the rice (Tillman *et al.*, 2002; Lakha *et al.*, 2005). Losses occurred mainly as leaching, denitrification, or volatilization and cause potential environmental harm, affecting ecosystem functioning (Tillman, 1999). Under these situations, increasing recovery efficiency of N per unit area through use of appropriate N management practices has become an essential component of modern rice production technology.

The origin of inorganic N in paddy soils can be described in terms of two reactions. The first occurs in a reduced soil environment, in which soil ammonium N (NH_4-N) originates from fertilizer or mineralized soil organic N. This NH_4-N is adsorbed by cation exchange sites such as clay minerals, or organic matter in soil, absorbed by rice, or immobilized by microorganisms. The NH_4-N is then relatively stable compared to NO_3-N (Ando *et al.*, 1978).

In the second reaction, NH_4-N is changed into NO_3-N at oxidized sites, and NO_3-N moves to reduced areas by diffusion or water flow. NO_3-N is easily changed into N_2 gas in a reduced environment, which is the mechanism of N lost from the paddy ecosystem (Patrick and Reddy, 1976). If N loss increases under an aerobic condition the recovery efficiency of N by rice plants might be reduced and thus the yield level might be also reduced.

Therefore, evaluation of fate of N under water-saving management should be needed.

1.5 Water-saving irrigation practices

Many studies on water-saving irrigation managements have been conducted (Li, 2001; Bouman and Tuong, 2001; Mao, 2001; Tabbal *et al.*, 2002; Belder *et al.*, 2004) such as (1) MSD, (2) intermittent irrigation followed by shallow water management (Thakur *et al.,* 2010); (3) shallow water depth (SWD) (Lin *et al.*, 2004); (4) alternate wet and dry (AWD) periods throughout the crop cycle (Satyanarayana *et al.*, 2007); (5) internal drainage (Ramasamy *et al.*, 1997); (6) continuous soil saturation (Borrell *et al.*, 1997) and others.

1.5.1 Short term drainage

MSD involves the removal of surface flood water from the rice crops for about seven to ten days. The duration of the dry period must be long enough for rice plant to experience visible moisture stress. MSD aerates the soil, interfering with anaerobic conditions and seems to be short term drainage (Nelson *et al.*, 2009). MSD, which will cause anaerobic and aerobic cycling, are considered to be options for reducing CH_4 emission from paddy field (Wassmann and Pathak, 2007) and also be practiced for conserving water. In addition, drainage may affect the efficiency of N fertilizer for lowland rice as I mentioned before. In addition, drainage inhibits ineffective tillers and improves root activities (Zou *et al.*, 2005). CH_4 emission reductions associated with drainage in rice field (Wassmann and Pathak, 2007). According to Mori and Fuji, (2007) the timing of drained condition and duration of drainage might also affect N uptake and rice growth, but information about timing of drainage condition and duration of drainage is limited.

1.5.2 Long term drainage

Long term drainage can be one better option for both reducing CH_4 emission and water saves. Other 'water-saving' irrigation techniques, long term drainage has been introduced (Guerra *et al.*, 1998) to denominate irrigation strategies by i) keeping the soil just saturated or ii) alternate wetting /drying, i.e. allowing the soil to dry out to a certain extent before re-applying irrigation water, iii) delayed flooding etc.

1.5.3 Alternate wetting and drying (AWD)

The International Rice Research Institute (IRRI) in the Philippines has developed AWD water management to mitigate CH_4 emission from paddy field (IRRI, 2009). AWD also can use to reduce their water consumption in irrigated fields. Rice fields using this technology are alternately flooded and dried. The number of days of drying the soil in AWD can vary according to the type of soil and the cultivar from 1 day to more than 10 days. Large reductions in CH_4 emissions are possible using AWD compared to continuous flooding. It will help the economic use of water during rice cultivation.

1.5.4 Saturated soil culture

In saturated soil culture (SSC), the soil is kept as close to saturation as possible, which decreases the seepage and percolation flows. Although conceptually sound, SSC will be difficult to practically implement since it requires frequent (daily or once every two days) applications of small amounts of irrigation water to just keep a standing water depth of 1 cm (IRRI, 2009). Saturated soil culture (SSC) for rice production has been reported to reduce water use by 25-50% without any significant yield loss (Subramanian *et al.*, 1978; Jha *et al.*, 1981; Tabbel *et al.*, 1992). This method involves keeping the soil saturated with no standing water throughout the rice growing season.

1.5.5 Delayed flooding

Delayed flooding involves intermittent irrigation of the crop until about ten days before panicle initiation (PI) stage. The timing and number of irrigations will be determined by the growing season's temperatures (Norman *et al.*, 1992). Delayed flooding in lowland rice systems reduced water consumption without sacrificing yield in several studies (McCauley and Turner, 1979; Beyrouty *et al.*, 1992; Norman *et al.*, 1992). Lilley and Fukai (1999) suggested that yields should not differ between delayed flooded rice and flooded rice during the entire season as long as the non-flooded period does not stress the rice plant. Grigg *et al.* (2000) found that the duration of the flood before and after the reproductive period had no appreciable effects on grain yield or quality.

1.5.6 Controlled irrigation

According to Guerra *et al.* (1998), water management was conducted under controlled irrigation (shallow water depth) and intermittent irrigation (Non-flooding) was applied to keep the paddy field moist and prevent water from standing after the panicle initiation stage. This water management is similar to the water management strategy for the system of rice intensification (SRI). This practice has been proven to be effective in saving water without causing yield reduction (Yu and Zhang, 2002).

1.6 Effect of drainage on N loss and root physiology activity

During the aerobic period of alternate flooding, NH_4-N is rapidly nitrified due to the availability of oxygen in the soil pores (Chowdary, 2004). Nitrification provides the substrate (NO_3-N) for denitrification when the soil is re-flooded (Broadbent, 1971). The N losses increased because of nitrification–denitrification processes induced by drying (Sah and Mikkelsen, 1983; Buresh *et al.*, 1993) and drainage rice systems have greater potential for N losses (Vial, 2007). In addition, the drying phase of rhizosphere will help root growth and its sustainability for water transport to rice plants even under low soil moisture conditions.

With a constant root zone, moisture content controlled under shallow water management, supplemental O_2 gas and heat are continuously provided to the soil to supply the physiological water demand of root, thus making the soil environment more suitable for rice root growth (Liu and Huang, 2005). The specific heat of water is 1 calorie per gram whereas the specific heat of the soil is about 0.2 calorie per gram. This means it takes five times more energy to raise the water temperature than the soil temperature. Or, with the same energy input, the soil temperature will increase five times more than the water temperature (Peng *et al.*, 2004). Similarly, soil temperatures might have increased the mineralization rate of soil organic N at later growth stages and resulted in greater amount of mineralized N for SWD (Van Cleve *et al.*, 1990). Another some report support the effect of enhanced root and microbial respiration on soil solution chemistry and plant nutrition is determined to a large extent by the buffering capacity of the soil (Olson, 1963). Mishra *et al.* (2006) argued that shallow water depth (SWD) practice could be a major reason for the enhanced root activity in rice plants under shallow water management. Another report argued that one potential mechanism for enhanced root growth in warmer soils is the source-sink relationship between above-ground and below-ground plant parts (Day *et al.*, 1991). Elevated soil temperatures are known to increase the rate of photosynthesis (Day *et al.* 1991, Schwarz *et al.*, 1997). Higher rates of photosynthesis increase the availability of fixed carbon, some of which is translocate below ground to sustain new root growth (Kramer and Boyer, 1995). Other possible causes of enhanced root growth with increasing soil temperatures are higher production of growth regulation substances (e.g., abscisic acid, cytokinins, gibberellins, etc.) and changes in the relative proportions these substances (Aktin *et al.*, 1973, Bowen, 1991). Thus, water-saving irrigation techniques have several benefit factors for lowland rice but actual factors are still unknown. Earlier most of the studies were concentrated to water consumption and yield but the information about the fate of N in paddy field under different water-saving practices is still very poor.

1.7 Objectives of the study

The objectives of the study are: i) NH_4-N converted to NO_3-N and NO_3-N further denitrified as N_2 gas and ii) maintain/ promoting root physiological activity and these phenomena i) reducing non-productive tillers and ii) increasing lodging resistance.

For these above purposes, MSD could be performed well as to keeping oxidative soil condition and NH_4-N converted to NO_3-N in paddy field as we assumed. But is MSD really converted to oxidative soil condition under short term drainage? In addition, MSD could promote root physiological activity or not?

Similarly, Non-flooding water management could perform better than MSD because of longer drainage period as we assumed but real concept is unknown. Long term drainage could be performed well as keeping oxidative soil condition and should be converted NH_4-N to NO_3-N in paddy field. Under this situation, N use efficiency should be reduced but the result of this study found different concept and can be expected to save water and reduce CH_4 emission. On the other hand, controlled irrigation (SWD) could be performed well as SRI. Though SWD is a reductive soil condition, it enhanced rice root physiological activity and yield too because SWD could be performed well to kept warm soil temperature entire growth period than conventional practices (flooding) (Kramer and Boyer, 1995). Thus, rice plant uptake much N from both soil and fertilizer sources. SWD also has been proven to be effective in saving water (Hadi *et al.*, 2010). SWD can be expected to reduce CH_4 emission, too (Yang *et al.*, 2004). The fate of N fertilizer, rice growth and yield under water-saving management practices is still poorly studied. Therefore, this study was conducted-

a) To examine the impacts of different irrigation practices on the N uptake and root activities

b) To evaluate an irrigation system to save water and grain yield of rice

1.8 Structure of the dissertation

This dissertation is consists of an introduction (chapter 1), two research parts (chapter 2-3), and a general discussion (chapter 4). Chapter 2 focuses mainly short term drainage on N uptake and root activity of rice while chapter 3 focuses mainly long term drainage and SWD practices on fate of N, root physiological activity and yield of rice. Chapter 1 represents general introduction

Chapter 2 represents an effect of MSD on root physiological activities, N uptake and yield of rice in North East Japan:

1. Climatic condition and soil moisture percentage
2. N uptake
3. Root respiration
4. Xylem exudation
5. Root mass density
6. Yield and yield components

Chapter 3 deals with the early and middle growth-stage water management effects on the fate of inorganic N, growth and yield in rice

1. Climatic condition in the 3 year cropping
2. Soil Temperature
3. Water consumption
4. Active iron in soil
5. Exchangeable NH_4-N in soil
6. Tiller number and plant height
7. Above-ground biomass
8. Xylem exudation
9. N uptake originated from sigmoid type slow-release fertilizer
10. SPAD value
11. N uptake

12. Yield and yield components.

In the general discussion in chapter 4 the prospects and limitations for a comprehensive assessment of the impact of water-saving on yield, fate of inorganic N is discussed. Furthermore, the main conclusions are presented.

CHAPTER 2

Effect of Mid- Drainage on Root Physiological Activities, N Uptake and Yield of Rice in North East Japan

2.1 Introduction

Water-saving technologies can reduce methane emissions in a given area of rice land. The saved water will then be used to irrigate more land as new crops in future seasons (Wassmann *et al.*, 2000).

Generally rice was cultivated with flooding during the most growing periods. The main benefit of flooding is weed control. However, many findings have proved that more water during the early growth stage results less aeration, less ion transport, slowing down of metabolism, stoppage of microbial activities, and accumulation of salt in root zone and hampers the root development which ultimately affects entire growth and development of rice plant (Arashi, 1956). Therefore, water-saving irrigation techniques for making plant roots healthy are important.

Mid-Season Drainage (MSD) conventional cultural practice and short term drainage in Japan involves the removal of surface water from the crop for about 7 or more than 7 days towards the end of tillering. It can be considered that the MSD has to protect roots from various damages caused by the reductive condition of soil due to the shortage of oxygen in soil and to increase the activity of roots.

In addition, MSD reduced water use, creates unsaturated soils condition. MSD is an effective option for mitigating net global warming potential although 15-20% of the benefits gained by decreasing methane emission were offset by increasing N_2O emissions (Zou *et al.*, 2005).

In North East Japan (Yamagata prefecture) during MSD, there are many rainfalls (Japan Metrological Agency, 2009-2010) and that much rainfall affects the soil drying delaying or keeping moisture like a conventional flooding. Under these conditions, effect of MSD on root physiological activity was not understood.

For minimizing much rainfall effect, early mid-season drainage (EMSD) could better ways to solve that problem and might be expected to decrease soil moisture significantly from the field because during EMSD less rainfall occurred. The timing of drained condition and duration of drainage also affect rice growth and root health, but information about above mentioned is limited.

Many scientists mentioned that MSD has both positive and negative effect. Goto *et al.*, 2000 mentioned high yield in MSD where Mizuguchi *et al.*, 1992 mentioned MSD reduced yield. During vegetative stage water stress usually affects the growth and consequently decrease yield (Botwright Acuna *et al.*, 2008) and also agree with Mori and Fuji, 2007.

MSD increase root respiration rate and root oxidation power (Yamada and Ota, 1961); increase leaf photosynthetic rate (Koyama *et al.*, 1962); and leaf longevity (Iida *et al.*, 1990).

Root respiration and sap exudation rate are useful index of root physiological activity. Root respiration is closely linked to energy intensive uptake, reduction and assimilation of nitrate and ammonium ions (Bloom, 1992) and to active water uptake (Hirasawa *et al.*, 1983; Lee *et al.*, 1994; Yamaguchi *et al.*, 1996). Xylem exudation represents active water uptake capacity (Yamaguchi *et al.*, 1996).

Many findings of field experiments proved that MSD has both positive or negative effect on yield, positive effect on root physiological activities and negative effect on N uptake. Actually yield level is depends on root activities and N uptake of rice and varied with them and need to make balance.

Therefore, this study was conducted to know 1) the combined effect of water management, such as MSD on root physiological activities, N uptake and yield 2) the effect of EMSD on root physiological activities, N uptake and yield of rice in the year of 2009 and 2010.

2.2 Materials and Methods

2.2.1 General Information

Field experiments were conducted in Yamagata University Experimental Farm, Tsuruoka, Japan in 2009 and 2010. The soil properties were as follows: sandy loam with a pH of 5.1, CEC of 15.1 cmol(+) kg^{-1}, total-N content of 2.4 of g kg^{-1}, organic-C content of 25.7 g kg^{-1}, available P_2O_5 and exchangeable K_2O of 0.17 and 0.13 g kg^{-1} soil, respectively.

2.2.2 Cultural Practices

Chemical fertilizer (60 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1}) were applied as basal fertilizer in 2009 (7 May) and 2010 (8 May). All of the basal fertilizer was incorporated into the soil and pudding was done. Twenty kilograms of N (as NH_4-N) ha^{-1} and K (as K_2O) ha^{-1} were applied as top-dressing at the panicle initiation stage in each years. Generally in this Yamagata prefecture, K is not a limiting nutrient for rice yield though Japan Agriculture (JA) recommended the farmers to apply K fertilizer. Two major points are consideration for applying K fertilizer as a top-dressed: i) at PI stage, sole N top-dressed application enhanced rapidly to uptake by the plant but if this time K nutrients are available in soil, it is difficult to plant for uptake much N. The N and K nutrient combination in soil solution is not easier for uptake N much and thus ultimately rice plant uptake N slowly and that slow uptake reduce lodging risk ii) for maintaining eating quality, Mg and K ratio is very important for rice, application of top-dressed K fertilizer enhanced that ratio and thus rice uptake much both nutrients by rice plant. Seedlings (*Oryza sativa* L., c.v. Sasanisiki) at about three and half leaf stage were transplanted on May 14 in 2009 by manually and May 17 in 2010 by mechanically (30 x

15 cm). Average four seedlings were planted on each hill in 2009 and 2010. All of the cultural practices except water management were followed by conventional cultural practices in local area of Shonai plain, NorthEast Japan.

2.2.3 Treatments

The experiment consisted of three treatments with three replications mentioned as flooding from transplanting to 20 days before harvest (Flooded), mid-season drainage (MSD) and early mid-season drainage (EMSD). In flooded treatment, the water level was kept at depth of 5-6 cm in both years. In MSD drainage from June 25 to July 5 {42 days before heading (DBH) to 32 DBH)} and June 21 to July 1 (45 DBH to 35 DBH) were carried out in the year 2009 and 2010 respectively In addition, drainage from June 15 to July 5 (52 DBH to 32 DBH) was carried out in EMSD in the year 2009 (EMSD20) and drainage from June 14 to June 24 (52 DBH to 42 DHB) was carried out in EMSD in the year 2010 (EMSD10). In the both year, the duration and timing of EMSD was different as because to compare the relatively long and relatively short drainage either affect on rice root physiological activities or not.

All the plots were arranged in Latin Square (LS) design with 3 replications. The dimensions of the plot were 28 m length and 8 m width.

2.2.4 General Sampling

Plant N uptake was determined periodically from 5 weeks after transplanting to heading stage. The interval between samplings was less than two weeks. Average rice plant (tiller number same as average growth plant in treatment) in two hills per plot was used for N analysis. N content in each sample was determined by Kjeldahl method (Keeney and Nelson, 1982; Bremner and Mulvaney, 1982).

Harvesting was done from 2.7m^2 plots (equivalent to 60 hills) from undisturbed central area of the plot for yield measurement. After counting each panicle number of hills, ten hills based on average were selected for yield components and remaining 50 hills were harvested for yield examination.

2.2.5 Measurement of Root Respiration (Yamaguchi method)

Root respiration was measured in the year 2009 (38, 31 DBH, and 11 days after heading (DAH)) and 2010, (43, 36, 24 DBH, and 7 DAH), respectively. Two hills (average rice plants) per plot were taken using a monolith (30 cm long, 15 cm wide and 15 cm high) method for the analysis of root respiration. A monolith was placed on one hill and roots were carefully washed and after washing, roots were cut immediately for measurement (Yoshida, 1981). According to the method of Yamaguchi *et al* (1996), root respiration was evaluated as follows.

Barium solution [12.878 g $Ba(OH)_2$ plus 1.172 g $BaCl_2$ into 1L distilled water], Oxalic acid (0.045 mol) and 0.1% phenapthelien indicator solution were prepared. Immediately weighed about 8 g fresh small pieces of root and then inserted into small net pocket with cotton thread. Ten ml Barium solution contained conical flask with net pocket was air tight with cork and incubated for 2 hours and then titrated by oxalic acid solution.

2.2.6 Measurement of Xylem Exudation

Xylem exudation rate was measured in the year 2009 (38, 31 DBH, and 11DAH) and 2010 (37, 23 DBH and 8DAH (almost same date of measuring of root respiration)) respectively using the method of San-Oh *et al.* (2004). Plants in two hills per plot were cut 10 cm from the soil surface and pre-weighed absorbent cotton in plastic bag was attached to the cut end of each stem with rubber bands. To immobilize the cotton and avoid vaporization, the cotton was covered with a plastic bag. After 2 hours, each bag was detached, sealed and weighed, and the weight of the exudates was calculated by subtracting the weight of the bag and pre-weighed absorbent cotton.

2.2.7 Measurement of Root Mass Density

To measure root mass density, roots were taken from the field using the monolith method (average rice plant 2 hills per plot) at 2 week intervals between the times of after 5 weeks transplanting to heading stage. Root mass density was measured by the water displacement method of putting all roots in a measuring area (Zhang *et al.*, 1994).

2.3 Results

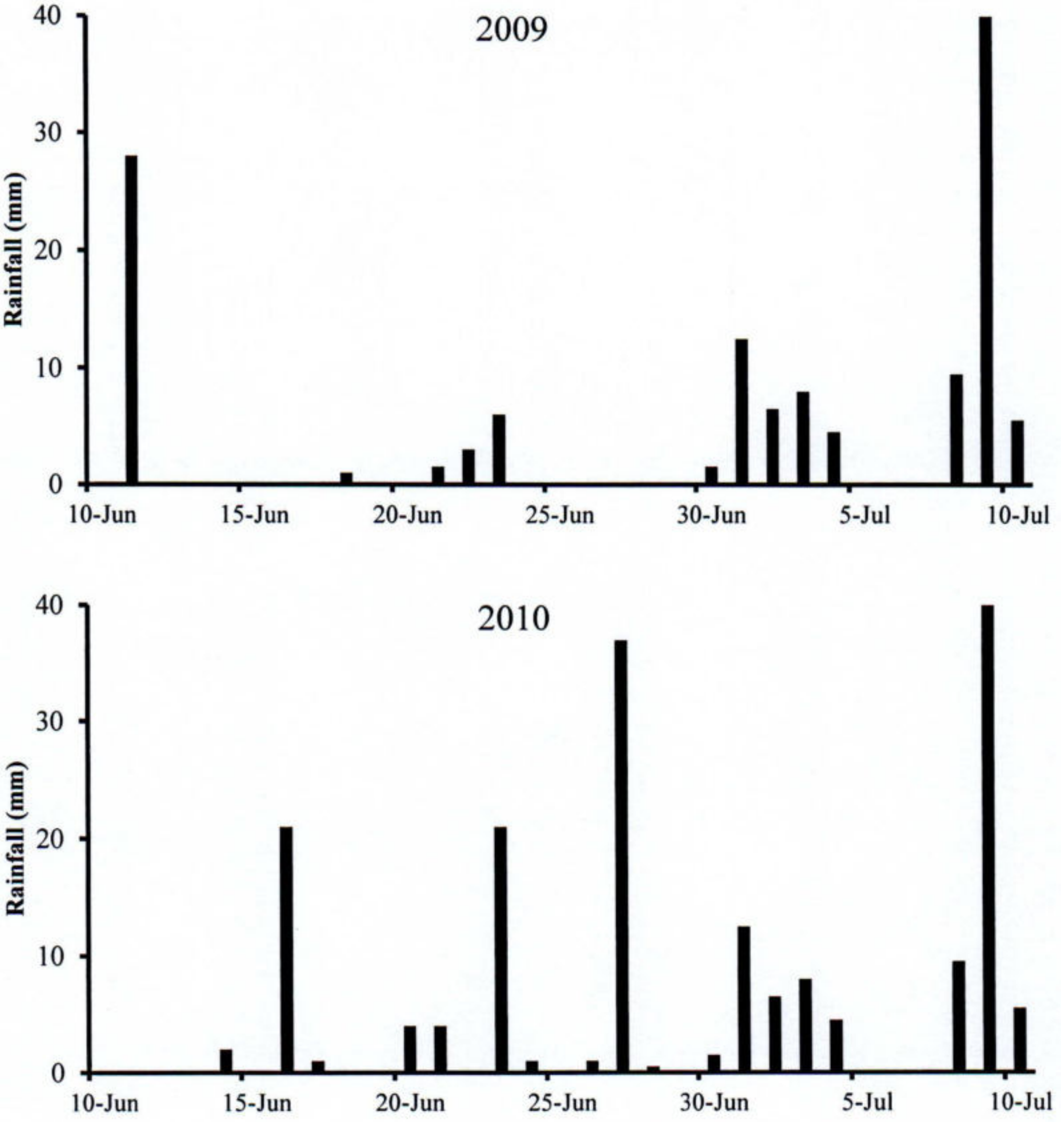
2.3.1 Rainfall and Soil Moisture Percentage:

Figure 2-1 showed the daily rainfall of Tsuruoka in the year 2009 and 2010. Drainage from June 25 to July 5 was carried out in MSD in 2009. Total rainfall was 33.0 mm from June 25 to July 5 in 2009. On the other hand, from June 21 to July 1 was carried out in MSD and during that time total rainfall was 73.5 mm in 2010.

Additionally, drainage from June 15 to July 5 was carried out in EMSD20 and 72.5 mm rainfall was recorded in the year 2009. Drainage from June 14 to June 24 was carried out in EMSD10 and recorded total rainfall was 54 mm in the year 2010.

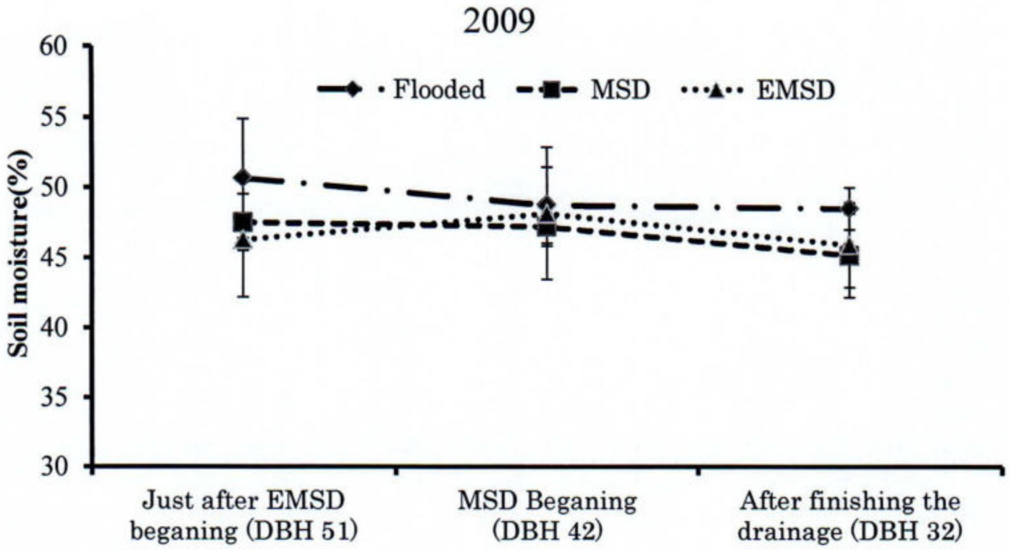
Fig. 2-2 indicated the soil moisture percentage (V/V) of fresh soil of the year 2009 and 2010. After MSD beginning and after finishing the drainage treatment soil moisture content of MSD had no apparently different than Flooded treatment in 2009 and 2010 as because during that time rainfall occurred so that the dryness of the drained field was not so dried.

On the other hand, in 2009, just after EMSD beginning the soil moisture were 50.7%, 46.3% and 47.5% in Flooded, EMSD20 and MSD and 53.3%, 49.8% and53.0% in Flooded, EMSD10 and MSD in the year 2010, respectively. Though statistically had no significant different, the dryness tendency was higher in both EMSD20 and EMSD10 than MSD and Flooded treatments from field observation in this study. EMSD20 and EMSD10 treatment showed many soil cracks than MSD treatment during field observation period.



Source: Japan Metrological Agency, 2009-2010

Fig.2-1. Daily rainfall (mm) of the month of June and July in the year 2009 and 2010



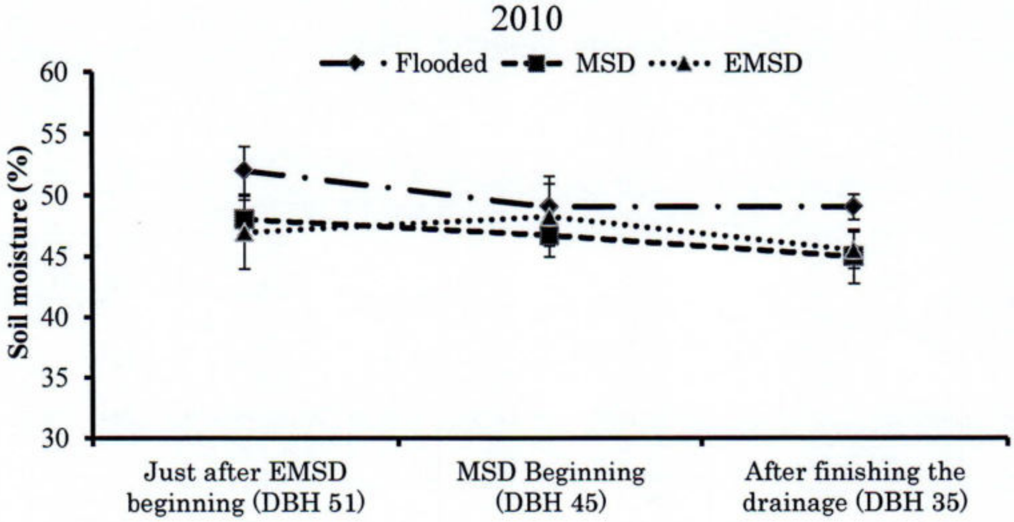


Fig.2-2. Soil moisture percentage during the drainage time in the year 2009 and 2010 Flooded: continuous flooding, MSD: mid-season drainage, EMSD: early mid-season drainage, DBH: days before heading

2.3.2 N Uptake in Plant

Fig.2-3 showed that, in the year 2009 during 51, 46, 41 and 31 DBH the nitrogen accumulation in plant was almost same among the treatments. But MSD treatment showed little bigger value than other treatments and had no significant difference. In the year 2010, 41DBH showed the significant bigger amounts of N in plant in MSD than Flooding treatments and also 36 DBH showed the greater value than other treatments although no statistically significant differences.

Additionally, N uptake of EMSD20 in the year 2009 was larger than Flooded at 51 and 46 DBH and smaller than Flooded treatments at 41 and 31 DBH. N uptake of EMSD10 in the year 2010 was larger than Flooded at 46 DBH and smaller than Flooded treatments at 41 and 36 DBH, respectively.

2.3.3 Root Physiological Parameter

2.3.3.1Root respiration rate

The respiration rate of rice root was shown in Fig.2-4. The trend of respiration rate was higher in MSD than Flooded at 38 DBH and that at 31 DBH in MSD showed the significantly (5% level) higher value comparing to Flooded in the year 2009. The trend of root respiration rate was MSD>EMSD20>Flooded in 2009.

In 2010, the root respiration rate was higher in MSD at 36 DBH and 24 DBH. After that, the value of MSD and Flooded declined gradually and it was almost same at 7 DAH. (Fig.2-4). Respiration rate of Flooded at 36 DBH was significantly lower than MSD (5% level). At later stage, MSD showed the better performance than Flooded even though insignificant.

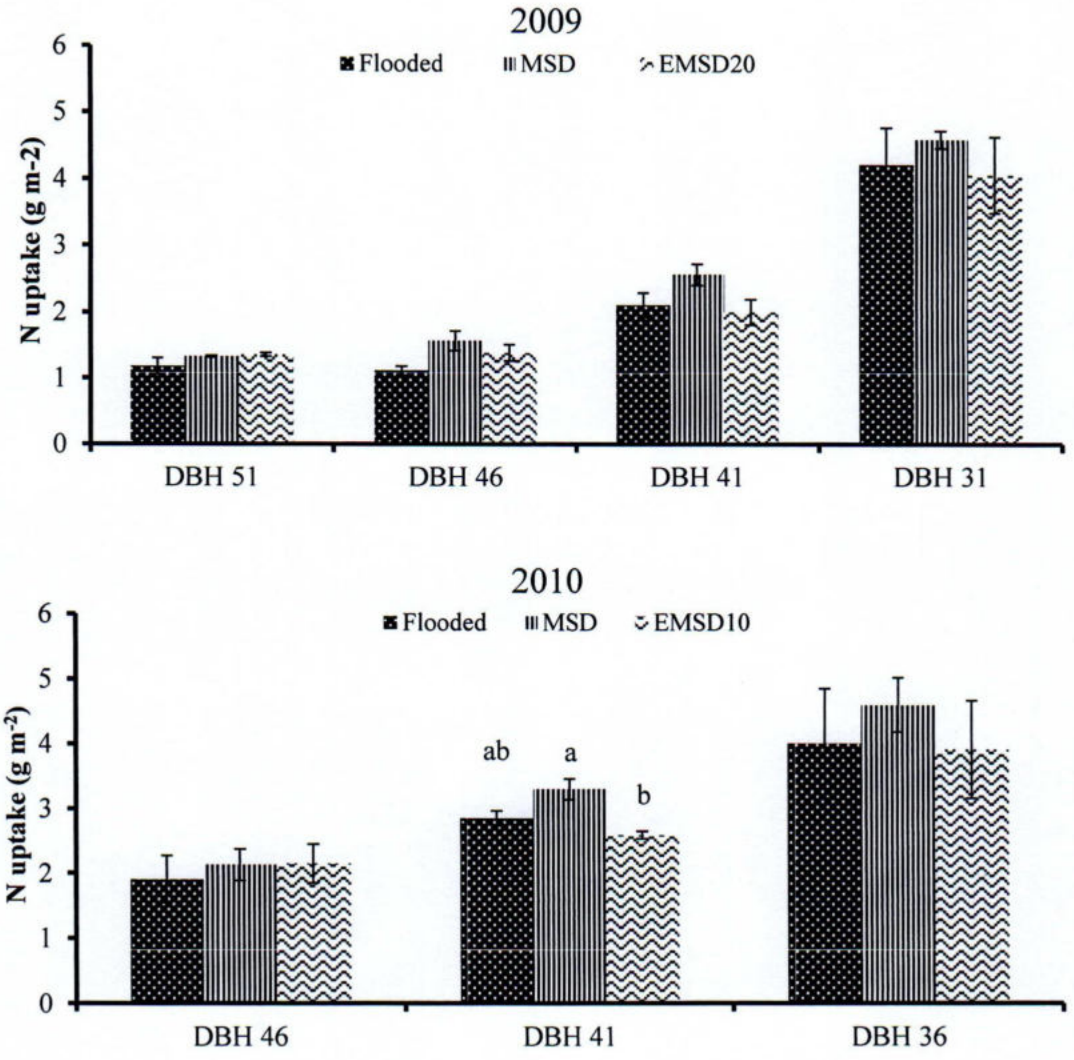


Fig.2-3. N uptake in plant at days before heading (DBH) in Flooded, EMSD and MSD treatments in 2009 and 2010, vertical represents standard error, Flooded: continuous flooding, MSD: mid-season drainage, EMSD20: early mid-season drainage 20 days, EMSD10: early mid-season drainage 10 days, DBH: days before heading

On the other hand, the trend of respiration rate of EMSD20 was higher than Flooded at 38, 31 DBH and had no significant different in the year 2009 and EMSD10 in the year 2010 was higher than MSD at 43 DBH but lower than MSD at 36, 24 DBH respectively.

2.3.3.2 Xylem exudation rate

Fig.2-5 showed the xylem exudation rate. Although no significant differences were observed between MSD and Flooded treatments in both years, the xylem exudation rate showed higher trend in MSD than Flooded at 38 DBH in 2009. In 2010, the trend of the MSD treatment showed the larger value than Flooded.

Additionally, the trend of xylem exudation rate of EMSD20 was smaller than MSD and higher than Flooded treatments at38, 31 DBH, 11 DAH in the year 2009 and EMSD10 in the year 2010 was similar than 2009.

2.3.3.3 Root mass density

Rice root mass density was shown in Fig.2-6. In 2009 the root mass density was higher in MSD at only after heading stage (11 DAH) and had no significant differences at 38 and 31 DBH. The same trend was occurred in 2010.

On the other hand, the trend of root mass density of EMSD20 or EMSD10 was almost same at different days before and after heading in the both years.

2.3.3.4 Yield and Yield Components

There was no significant difference in brown rice yield among the treatments in the year of 2009 and 2010. In the year 2009, the brown rice yield of MSD treatment was very low because of lodging immediately after the flowering stage (Table 2-1). The grain yield in the same experiment was 664 g m^{-2} for Flooded. In the year 2010, the brown rice yield of

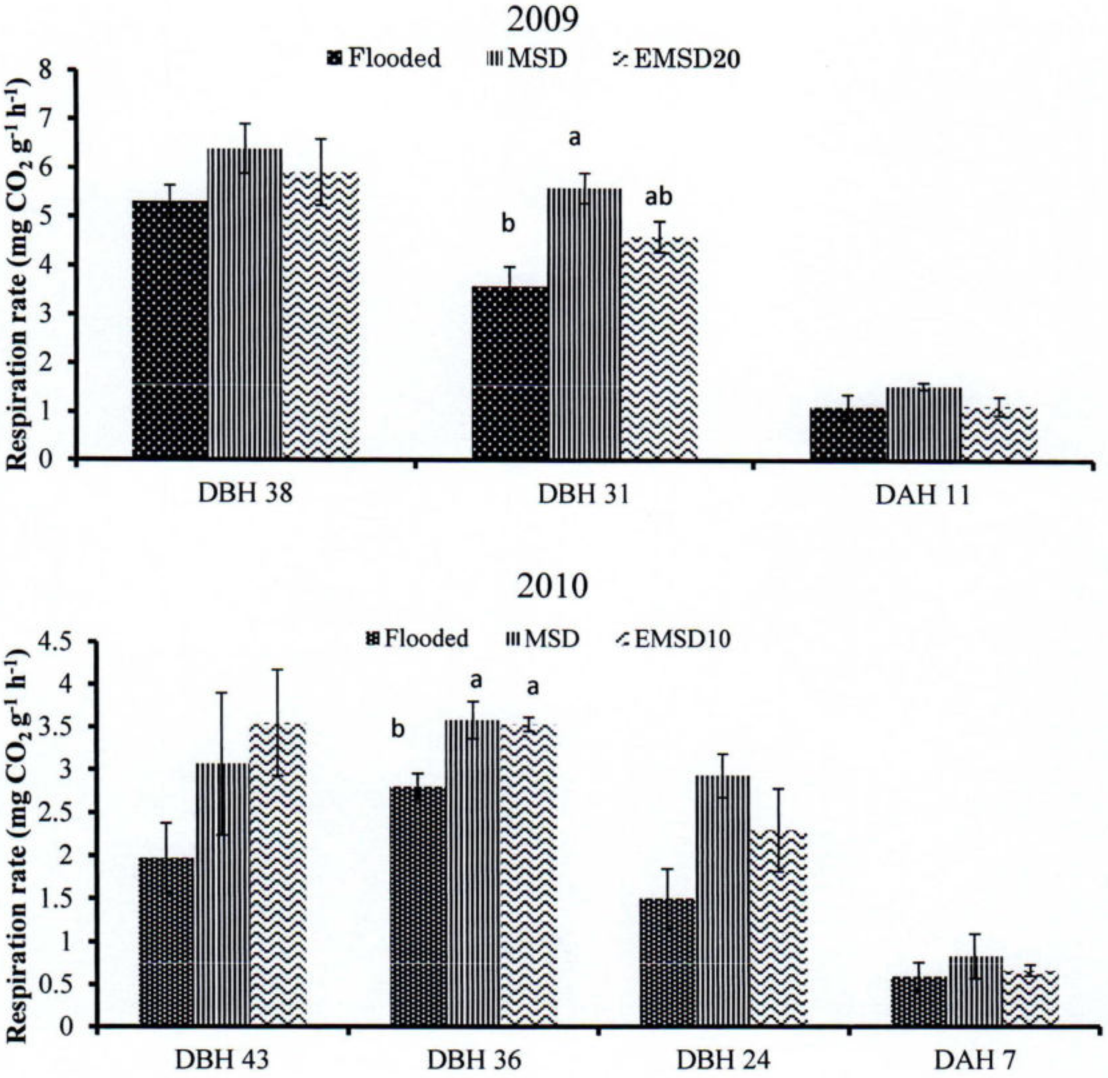


Fig.2-4. Root respiration rate (mgCO_2 DWg^{-1} h^{-1}) at DBH 38, 31, DAH 11 and DBH 43, 36, 24, DAH 7 in flooded, EMSD and MSD treatments in 2009 and 2010, vertical bar indicates standard error, Flooded: continuous flooding, MSD: mid-season drainage, EMSD20: early mid-season drainage 20 days, EMSD10: early mid-season drainage 10 days, DBH: days before heading, DAH: days after heading

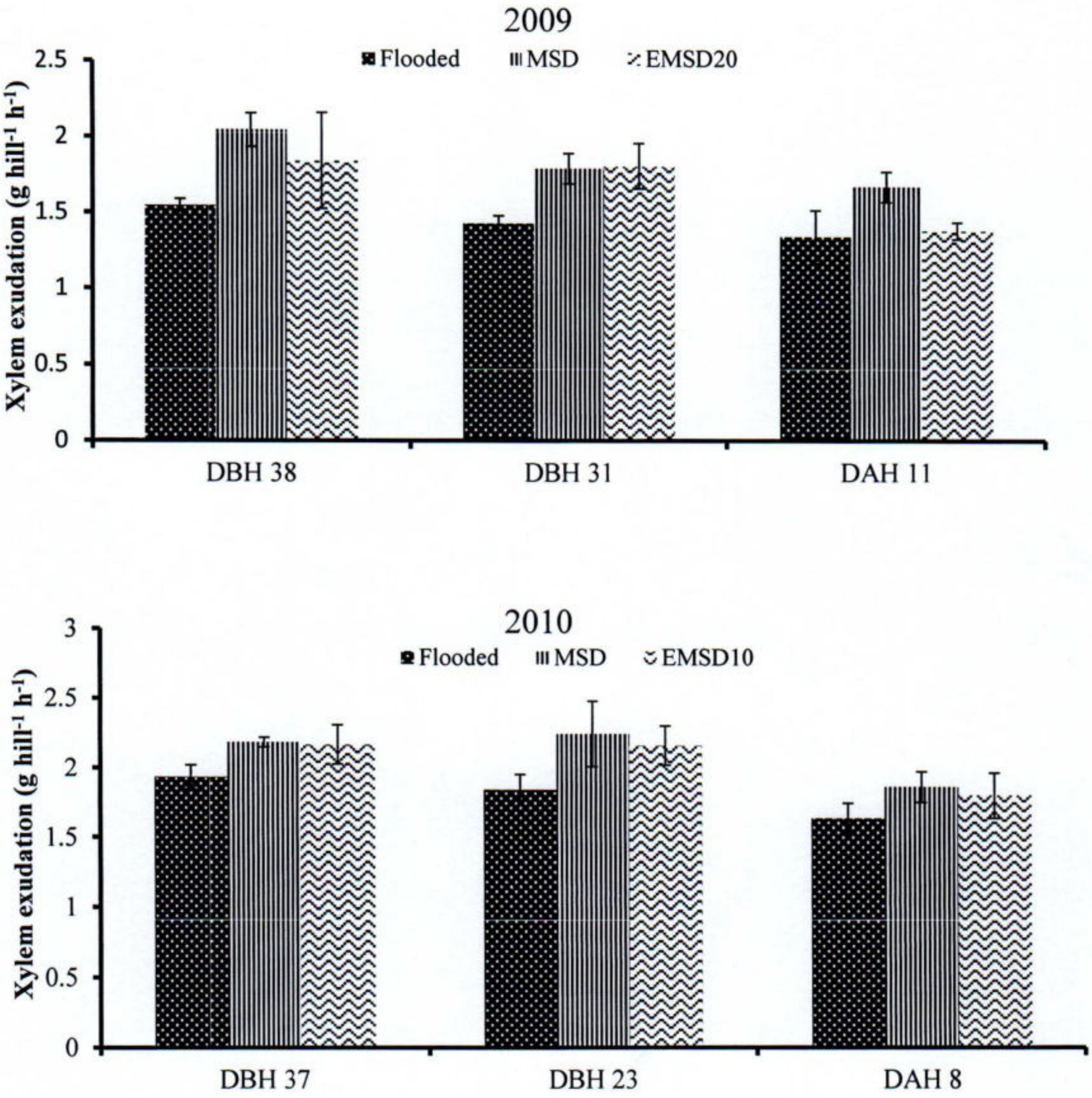


Fig.2-5 Xylem exudation rate at DBH 38,31, DAH 11 and DBH 37, 23, DAH 8 in flooded, EMSD and MSD treatments in 2009 and 2010, vertical bar indicates standard error, Flooded: continuous flooding, MSD: mid-season drainage, EMSD20: early mid-season drainage 20 days, EMSD10: early mid-season drainage 10 days, DBH: days before heading, DAH: days after heading

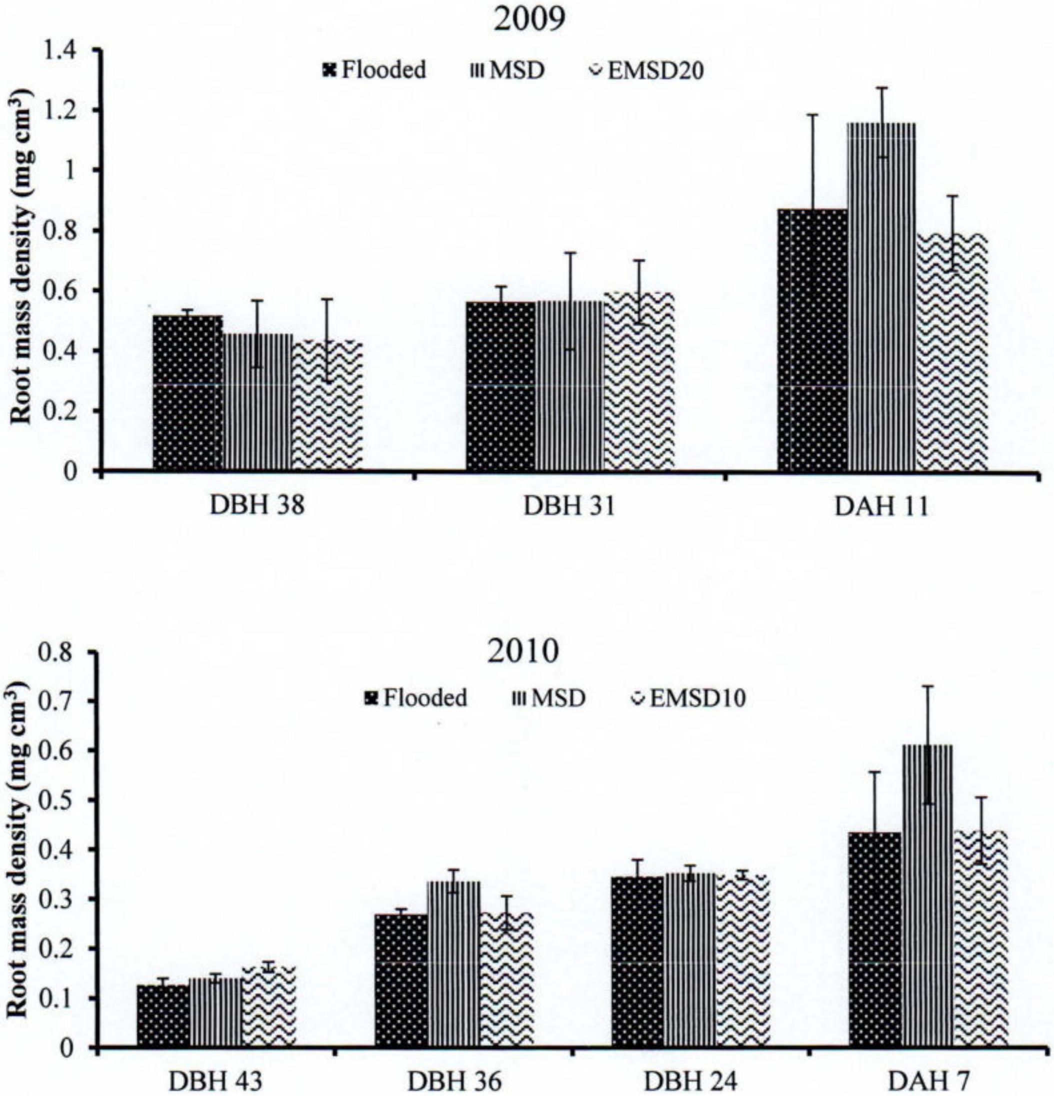


Fig.2-6. Root mass density (15cm) at DBH 38, 31, DAH 11 and DBH 43, 36, 24, DAH 7 in flooded, EMSD and MSD treatments in 2009 and 2010, vertical bar indicates standard error, Flooded: continuous flooding, MSD: mid-season drainage, EMSD20: early mid-season drainage 20 days, EMSD10: early mid-season drainage 10 days, DBH: days before heading, DAH: days after heading

MSD (653 g m^{-2}) treatment was larger than Flooded (635 g m^{-2}) treatments. The number of spikelets per m^2 tended to be larger in flooded treatment than MSD treatment in the 2009 but in the 2010 the opposite trend was observed. The number of panicles m^{-2} in MSD smaller than Flooded treatments in 2009 and same trend was observed in 2010. The number of spikelets m^{-2} in Flooded was 36,000 and 35,000 which was 75% and 102% of that in MSD in 2009 and 2010. The number of spikelets m^{-2} of MSD treatment was significantly smaller than Flooded in 2009 but in 2010 the treatments did not show any significant differences. The difference in 1000-grain weight between the treatments was negligible.

In addition, yield and yield components data indicate that drained duration (EMSD20 or EMSD10), drained timing (EMSD and MSD) and drainage (MSD and Flooded) had no adverse effect on yield. The grain yield of EMSD20 was 594 g m^{-2} which was larger than MSD but smaller than Flooded treatments in the year 2009. On the other hand, the brown rice yield of EMSD10 (623 g m^{-2}) was smaller than MSD and Flooded treatments in the year 2010.The number of spikelets per m^2 tended to be smaller than Flooded and MSD treatments in the both years. The number of panicles m^{-2} in EMSD20 smaller than Flooded and MSD respectively in 2009 where in 2010, the number of panicles m^{-2} showed the opposite trend. The number of spikelets m^{-2} of EMSD20 and MSD treatment was significantly smaller than Flooded in 2009 but in 2010 the treatments did not show any significance differences.

2.4 Discussion

Soil moisture among the treatments and the between the both year showed the same trend and statistically had no significant different. As observed in this study the dryness tendency was higher in MSD than Flooded. Drainage supply oxygen to soil (Stoop *et al.*, 2002) and root activities or root mass might be affected by oxygen supplied although no significant different in soil moisture among the treatments.

Drainage (MSD and EMSD20 or EMSD10) is believed to improve oxygen supply to rice

Table 2-1 Brown rice yield and yield components

Year	Treatment	Brown rice yield ($g\ m^{-2}$)	Panicle no. (m^{-2})	Spikelet no. ($Panicle^{-1}$)	Spikelet number ($x\ 10^3\ m^{-2}$)	Ripened grains (%)	1000- grain wt. (g)
2009	Flooded	664±599	475±19	76±0.9	36±1a	76±5	23.6±0.1
	MSD	534±152	433±19	62±2	27±0.2b	82±1	23.8±0.1
	EMSD20	594±128	391±30	72±5	28±1b	87±3	24.1±0.1
	P-value	0.112	0.113	0.077	0.003	0.211	0.083
2010	Flooded	635±192	495±19	67±5	35±2	79±2	22.7±0.6
	MSD	653±511	481±32	70±5	34±5	84±4	22.9±0.6
	EMSD10	623±123	510±12	62±2	32±1	86±3	22.8±0.1
	P-value	0.813	0.692	0.516	0.747	0.425	0.967

Values represent mean of three replications ±standard error. Same letter in the same column are not significantly different. Flooded: continuous flooding, MSD: mid-season drainage and EMSD20: early mid-season drainage 20 days, EMSD10: early mid-season drainage 10 days roots, with potential advantages for nutrient uptake (Stoop *et al.*, 2002), and to avoid accumulation of toxic substances such as ferrous iron and hydrogen sulfide, which are potentially toxic to root growth (Hayashi *et al.*, 1960). Improved root condition increase in soil redox potential, which induces a prolonged synthesis and transport of cytokinins in roots and also extended photosynthetic activity, which may increase the deposition of carbohydrates in the grains and ultimately increasing the grain yield during maturity stage (Matsushima, 1971; Tanaka, 1972).

Root respiration was higher in MSD than Flooded treatment at neck node differentiation stage only (Fig.2-4). MSD might be due to better aeration during neck node differentiation stage and root system associated with higher mobility and absorption of inorganic N in soil solution which increased the uptake of nutrient and contributed to favorable growth attributes which in turn had resulted on higher yield attributes (Palachamy *et al*, 1989).

In addition, respiration rate of EMSD20 or EMSD10 in both years showed the same trend and lower than MSD treatments. During this stage oxygen can be supplied through the root and root becomes more active. Root activity parameters (root respiration) in drained condition (MSD and EMSD20 or EMSD10) tended to be higher than those in Flooded (though insignificant) at the maturity stage (Fig.4) in our experiment and this result was agreed with previous report (Osaki *et al.*, 2001).

EMSD20 and MSD treatments the yield and yield components were not statistically significant; it means prolonged drained field condition of one year data had no adverse effect on yield and yield components under unfertile soil. Mori and Fuji, 2007 mentioned that EMSD reduces the gain number than MSD under fertile soil in Shonai area but this research mentioned that prolonged drained (EMSD20) did not affect the growth and yield of rice under unfertile soil. Fertile and unfertile soil under different water management might be not same. Therefore, this study should be required further research for understanding the mechanism.

2.5 Conclusion

This research indicates that the drained field conditions (MSD) in North East Japan did not decrease N accumulation/uptake and induced higher root physiological activity by enhancing root respiration and xylem exudation rate during drainage period.

In addition, this research suggests that timing and duration of drainage might not be affected rice growth though several years' data should be needed for more confirmation.

CHAPTER 3

Early growth stage water management effects on the fate of inorganic N, growth and yield in rice

3.1 Introduction

In chapter 2, short term drainage focused mainly on N uptake, root activity and yield of rice. From this study I could not confirmed the influences of drainage on the fate of inorganic N, growth and yield, because drainage might not be altered the soil aerated condition from anaerobic condition. I could found some positive impact on root activity from short term drainage only. Long term drainage has some possibility to show the positive or negative impact on the fate of inorganic N, growth and yield of rice. In addition, both short and long term drainage can be one of the better options for both reducing methane emission and water saves (Guo and Zhou, 2007). Furthermore, controlled irrigation which is similar to the water management strategy for the system of rice intensification (SRI) has been proven to be effective in saving water without causing yield loss (Yu and Zhang, 2002).

Nitrogen (N) and water are two of the most important factors in rice production. Many studies have recommended continuous flooding during the early growth stages for rice production in Japan and during the whole rice growth stage for rice production around the world. However, improved water-saving management practices are needed, in rice production to reduce pressure on scarce water resources (Cassman *et al.*, 2002; Gilland, 2002).

Paddy fields are typically submerged and develop a reduced plowed soil layer and an oxidized surface soil layer (Patrick and Reddy, 1976; Hasebe *et al.*, 1987). Inorganic N transformations are also influenced by alternate aerobic and anaerobic conditions. Under certain conditions organic N is converted to NH_4-N, under aerobic conditions the NH_4-N is oxidized to NO_3-N and under anaerobic conditions the resulting NO_3 denitrified. Loss of N through sequential nitrification and denitrification is especially high in soils planted to lowland rice, where water management practices sometimes require frequent draining and re-flooding (Russel, 1981).

Water-saving practices can produce more aerobic soil conditions than continuous flooding conditions. Specifically, water-saving methods such as alternate wetting and drying (AWD) might be beneficial to root growth because they increase soil aeration, and may encourage N uptake by rice plants. Similar results have been reported for other study, and AWD has been reported to result in more nutrient uptake (especially N uptake), via enhanced root physiological activity (Rajesh and Thanunathan, 2003). With respect to the fate of inorganic N, it is believed that more NH_4-N might be denitrified and lost from the paddy ecosystem. Soil NH_4-N in all paddy soils largely disappears at the maximum tiller number stage and has been found in small or trace amounts after this stage (Ando *et al.*, 1978). This finding suggests that the fate of fertilizer, especially from basal N recovery by rice plants or loss through nitrification-denitrification, is affected by water management decisions made before the maximum tiller number stage.

Ando and Shoji, 1984 and Ando *et al.* (1996) observed that a proportion of top-dress N disappeared in the submerged water and the exchangeable soil NH_4-N in soil reached the maximum amount one day after N topdressing. Almost all of the exchangeable NH_4-N derived from top-dressed N was observed in uppermost layer (0-1 cm) of the Ap horizon, and absorption was largely finished 7 days after topdressing N. Plant ^{15}N recovery was determined to be about 50%. On the other hand, sigmoid type slow-release N fertilizer having releasing capacity not only uppermost layer but also the all of the Ap horizon layer, because application method was same as basal N (amendment to Ap layer) and distributed the root zone area properly during the middle rice growth. During middle growth rice stage sigmoid type slow-release N fertilizer starts to release N and within 100 days (25^0C) most of N is released from sigmoid type slow-release N fertilizer (Gandeza, 1991). Therefore, sigmoid type slow-release fertilizer labeled with ^{15}N was used to estimate the root physiological activity under different water management.

The fate of N fertilizer, rice growth and rice yield under water-saving conditions has not been well studied. Therefore, this study was conducted to examine the effects of various irrigation practices on rice N dynamics during the early and middle growth stages.

3.2 Materials and methods

3.2.1 General Information

Field experiments were conducted between April to September 2011 and 2012 at Takasaka (38° 43′ 18″ N, 139° 49′ 19″ E), which is located 4 km west of the agriculture faculty, experimental farm at Yamagata University, Tsuruoka, Japan. The soil, which is classified as an Aquent (according to the USDA classification system), had the following characteristics: clay loam with a pH of 5.1, cation exchange capacity (CEC) of 28.6 cmol (+) kg^{-1}, total-N content of 2.4 g kg^{-1}, total-C content of 25.7 g kg^{-1}, and available P_2O_5 (according to the Bray No.2 extracting solution method) (Bray and Kurtz 1945) and exchangeable K_2O of 0.17 and 0.13 g kg^{-1} soil, respectively.

For LPS-100, a field experiment was conducted in 2012 and 2013. The field site was the same as above general information.

3.2.2 Climatic Condition

The average temperature from transplanting to heading was 21.8°C in 2011, 21.7°C in 2012 and 21.8 °C in 2013, and the average temperature for the previous 30 years was 21.0°C. The average number of sunshine hours in 2011and 2013 were 189.4 and 190.3WJ m^{-2} lower than in 2012 (213.6 WJ m^{-2}), and the average number of sunshine hours for the previous 30 years was 184.4. These data show that the climatic conditions for the experimental years were almost same as the previous 30 years.

3.2.3 Treatments

The experiment consisted of three treatments with four replications in 2011, 2013 and three replications in 2012. The three treatments were designated as conventional irrigation (Flooding), Shallow Water Depth (SWD) and Non-flooding. From transplanting to 20 days after transplanting (DAT), a ponded water depth of 0.05-0.06 m was maintained for all the treatments to prevent transplanting shock and cooler temperatures. For the Flooding treatment, ponded water with of 0.05- 0.06 m was maintained from 20 DAT to 99 DAT, and the water were drained 20 days before harvesting. For SWD, a ponded water depth of 0.01-0.02 m was maintained from 20 DAT to 99 DAT, and the water was drained 20 days before harvesting. Water depths in the Flooding and SWD plot were monitored at intervals of one or two days using plastic rulers. Irrigation was conducted according to the planned water depths for the Flooding and SWD treatments. Water management of Non-flooding treatment was as follows: On 20 DAT, ponding water of the plots was drained by opening outlets of which height was set at same height as soil surface. The plots were irrigated (splash) again when the soil observed hairline cracks (the soil moisture percentage was about 40%). Outlets of these plots were always open until 57 DAT. After 57 DAT, plots were irrigated again and water depth of 0.01-0.02 m (the outlet of Non-flooding treatment was set at 0.02 m height from soil surface) was maintained until 99 DAT, and the water was drained 20 days before harvesting. The soil moisture content at a soil depth of 0.05 m was measured daily with a DM-18 (Takemura Electric Works. Ltd, Japan). After 57 DAT, a ponded water depth of 0.01-0.02 m was maintained until 99 DAT, and then the water was drained 20 days before harvesting. We also measured the consumption of water for each treatment during 2012 and 2013 without replication, using a flow meter and a water pump. The main plot was 24.6 m long and 14.1 m wide. Each field was further subdivided to create a ^{15}N application plot, which did not receive N basal fertilizer (mini plot, 14.1 x 8.2 m^2). In 2011, 2013 all the water regime plots were arranged in a randomized complete design (RCD), but in 2012, 4 replications could not be employed because of seedling damage, and those plots were arranged in a randomized design with 3 replications.

3.2.4 Manure and Fertilizer Application

Organic manure (compost) was applied at 10 ton ha^{-1} in 2011 (25 April), 2012 (26 April) and 2013 (30 April) and compound fertilizers (40 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1} and 40 kg K_2O ha^{-1}) were applied as basal fertilizer in 2011 (7 May), 2012 (9 May) and 2013 (10 May). All of the basal fertilizer was incorporated into the soil and puddling was done on 15 May 2011, 20 May, 2012 and 13 May 2013. Ten kilograms of N (as NH_4-N) ha^{-1} was applied as top-dressing at the panicle initiation stage in each year except in 2013. In the year 2013, the plant growth was too vigorous and assumed if it applied the same rate N fertilizer as a top-dressed, there is a great possibility occurring lodging. For minimizing lodging, thus applied half of N compares the general application rate.

For application of ammonium sulfate labeled with ^{15}N as basal N, wooden boxes (0.6 x 0.3 m) were set at a depth of 0.15 m in the middle of the mini-plot (the zero- N plot) just after transplanting, following the basal N application. To protect the field water inside the wooden boxes, plastic sheets were placed outside the boxes and water was removed from the wooden boxes with a plastic mug. Four grams of N m^{-2} labeled with 3 atom % $(^{15}NH_4)_2SO_4$ was applied to each wooden box and mixed thoroughly by hand with soil. Four hills per wooden box were transplanted.

In the main plot, N was applied as top-dressed after two hills per plot were selected, based on the average number of hills. The Plastic boxes (0.3 x 0.15 m) were set at a depth of 0.15 m, and plastic sheets were placed outside the plastic box. Before the commercial N fertilizer was applied as top-dressing, the boxes were covered with paper bags to prevent the commercial N fertilizer entering into the plastic boxes. After the commercial fertilizer was applied to the main plot, ^{15}N fertilizer was applied inside the plastic boxes.

For application of urea coated sigmoid type slow-release fertilizer (LPS-100) as basal N, wooden boxes (0.6 x 0.3 m) were set at a depth of 0.15 m in the middle of the mini-plot (the zero- N plot) just after transplanting, following the basal N application. To protect the field water inside the wooden boxes, plastic sheets were placed outside the boxes and water was removed from the wooden boxes with a plastic mug. LPS-100 of 0.9 g equivalent to 4 g N m^{-2} labeled with 3 atom % ^{15}N (urea form) was applied to each wooden box and mixed thoroughly by hand with soil. Four hills per wooden box were transplanted.

3.2.5 Seedling age, Variety, Spacing and Transplanting time

Three and a half to four leaf-age seedlings (*Oryza sativa* L., c.v. Sasanisiki) were transplanted using a 0.3 m × 0.15 m adjusted rice transplanting machine on 18 May 2011, 23 May 2012 and 16 May 2013.

3.2.6 Data Collection

Data loggers (Tidbit v2 Temp logger model 10385-C, MAN-UTBI-001, USA) were set at a soil depth of 0.02 m in all plots to measure soil temperatures.

Plant samples were taken from randomly selected areas containing 4 hills × 3 sets i.e., 12 hills from each plot at the maximum tillering (48 DAT) and heading stages (80 DAT) in 2011 and the maximum tillering (48 DAT) and heading stages (79 DAT) in 2012. The above-ground plant samples collected at the maximum tillering and heading stages were separated into leaves and shoots, and the panicles were also separated. These samples were dried at 80°C for 2 days.

Plant N contents were determined by the Kjeldahl method (Kenney and Nelson, 1982). The dried plant samples were milled using a Heiko vibrating sample mill (Model TI-100, Heiko Seisakusho Ltd., Japan). Finely grind samples were weighed (Approximately 0.5 gm. sample for shoot and panicles samples and approximately 0.4 gm. for leaf samples). These samples were digested with 10 ml H_2SO_4 to which 1 spoonful of a catalyst mixture of K_2SO_4:$CuSO_4$ (9:1) was added. A final digested volume of 100 ml was prepared, and a 10 ml solution was taken from that volume for distillation. The nitrogen content percentages of the leaf, shoot and panicle samples were measured separately and then determined the total nitrogen content percentage in the plants. This percentage was converted into gm. m^{-2} by multiplying it by the respective dry matter weights of leaves, shoots and panicles. ^{15}N plant samples (derived from ammonium sulfate and LPS-100) were collected at the maximum tillering (48 DAT in 2011 and 2012) and heading stages (80 and 79 DAT in 2011 and 2012) in each years and were analyzed using mass spectrometer (Thermo Scientific Flash 2000 and Con FloIV and Delta V plus, Isotope Ratio MS, Germany).

Plastic coring tubes (0.15 m long and 0.05 m in diameter) were used collect soil samples from the centers of 4 hills and 3 different places in each plot at 20, 29 and 48 DAT in 2011 and 24, 36 and 48 DAT in 2012. The amount of exchangeable ammonium N (NH_4-N) was extracted with a 1M KCl solution and evaluated by steam distillation (Bremner and Keeney, 1965). The same extracted solution was used to determine the total inorganic N by adding Deverda's alloy apart from magnesium oxide. The nitrate nitrogen content was determined by subtracting the exchangeable ammonium content from the total inorganic nitrogen content. The exchangeable NH_4-N derived from fertilizer was estimated using the same procedure as described above, but the soil samples were collected from wooden boxes at 20, 29 and 48 DAT in 2011 and 24, 36 and 48 DAT in 2012. The ^{15}N content was measured by the spectro-emission method (Kano *et al.*, 1974).

The active or free iron (Fe^{2+}) content of the soil was determined by the Debs method, as modified by Kumada and Asami (1958). Ten grams of fresh soil were measured into a 250 ml plastic bottle mixed with 100 ml of 1 M acetate buffer (pH 2.8), and left to stand for 20 minutes, with occasional shaking at room temperature. After the samples were thoroughly mixed, they were passed through dry filter paper. Depending on field condition, 0.5-1.0 ml of aliquot were transferred into a 20 ml glass tube by pipette and 1 ml of 1,-10-phenanthroline solution were also added. The glass tube was then filled with distilled water. For making calibration curve, 1 ml of 1 M acetate buffer (pH 2.8) solution, 0.1-1 ml of standard iron stock solution were transferred into a 20 ml glass tube by pipette and added 1 ml of 1,-10-phenanthroline solution. Finally the glass tube was filled with distilled water. The resulting absorbance was read at 522 nm and compared with the standard curve. Fe^{2+} was measured at 14, 24, 36 and 57 DAT in 2012.

Xylem exudation rates were measured in 2011 (at 42 and 80 DAT) and 2012 (at 39 and 79 DAT), according to the method described in San-Oh *et al.* (2004). Samples from two hills per plot that, had an average number of tillers or panicles for each plot, were cut 10 cm from the soil surface, and a plastic bag containing pre-weighed absorbent cotton was attached to the cut end of each stem with rubber bands. After 2 hours, each bag was detached, sealed and weighed, and the exudates weights were calculated by subtracting the weight of the bag and the weight of the absorbent cotton. The xylem exudation rate was expressed in mg $tiller^{-1}h^{-1}$. Three replicates were performed.

In 2011, all plants were harvested on 16 September, and in 2012, all plants were harvested on 18 September. Sixty hills (2.7 m^2) were harvested and 10 hills were selected from among the 60 hills, based on their averages, measurement of the yield components were carried out.

3.2.7 Determination of N Release Pattern from LPS-100

A 10 g fertilizer from LPS-100 was put individually inside the lady stocking and loosely tightened. Samples were replicated four times. At transplanting period for each year, these fertilizer materials were buried at one location in the field at a depth of 4-5 cm. Sampling was done at the same date with plant sampling.

N contents from LPS-100 fertilizer were determined by the Kjeldahl method (Kenney and Nelson, 1982). Then, the nitrogen content percentages were measured from LPS-100 fertilizer. N release at different growth stages was calculated based on initial N content of 10 g sample and its changes at sampling time.

3.2.8 Statistical Analysis

Analyses of variance (ANOVA) and Tukey-Kramer tests were conducted using the STATCEL-2 software. Microsoft Excel was used for correlation analysis and application of and other statistical functions.

3.3 Results

3.3.1 Soil Temperature

From 21 DAT to 57 DAT, water management practices differed between treatments as shown in Fig. 3-1. In this experiment, the total amounts of irrigation water used from 20 DAT to 57 DAT in the Flooding, SWD and Non-flooding treatments were 0.87, 0.54 and 0.25 m^3 m^{-2}, respectively. The total amounts of irrigation water used from 57 DAT to 99 DAT were 0.84, 0.57 and 0.58 m^3m^{-2} in the Flooding, SWD and Non-flooding treatments, respectively, and the total amounts of irrigation water used from 20 DAT to 99 DAT, were 1.71, 1.11 and 0.83 m^3m^{-2} in the Flooding, SWD and Non-flooding treatments, respectively. There were no great differences in the average soil temperatures among the treatments, but the maximum soil temperature was lower and the minimum soil temperature was higher for the Flooding treatment than for the SWD and Non-flooding treatments in both years. There were no great differences in soil temperatures between the SWD and Non-flooding treatments (Table 3-1).

3.3.2 Soil Moisture Percentage

Figure 3-2 indicates the fresh soil moisture percentages (V/V) in 2011 and 2012. In 2011, the soil moisture were 48.2, 46.8 and 44.7% in the early (just after the beginning of water management), middle and maximum tillering stages, respectively, for the Non-flooding treatment, 47.8, 46.9 and 47.0% in the early, middle and maximum tillering stages, respectively, for the SWD treatment, and 47.8, 46.0 and 49.3% in the early, middle and maximum tillering stages, respectively, for the flooding treatment. Similarly, in 2012, the

Table 3-1 Daily maximum, minimum and average temperature of soil during 21 to 57 DAT

	Soil Temperature (^0C) (21 DAT-57 DAT)					
Treatment	**Maximum Temperature**		**Minimum Temperature**		**Average Temperature**	
	2011	**2012**	**2011**	**2012**	**2011**	**2012**
Flooding	26.5	27.4	23.8	22.2	25.3	24.5
SWD	29.4	29.3	22.5	21.3	26.0	24.9
Non-flooding	28.8	28.9	22.0	20.3	24.9	23.9

Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded, DAT: days after transplanting soil moisture percentages were 47.3, 47.5 and 43.1% in the early, middle and maximum tillering stages, respectively, for the Non-flooding treatment, 47.8, 43.6 and 50.6% in the early, middle and maximum tillering stages, respectively, for the SWD treatment, and 47.4, 46.6 and 48.8%, in the early, middle and maximum tillering stages, respectively, for the Flooding treatment. Although the differences in the soil water contents between the plots were very small, the dryness trend was higher for the Non-flooding treatment in both years, based on the field observations.

Similarly during Non-flooding period, the soil moisture was around 40-42% (Fig. 3-3).

3.3.3 Active Soil Iron (Fe^{2+}) Content

The active soil iron (Fe^{2+}) content was the same for all the treatments in the early growth stage (14 and 24 DAT) and then declined sharply in the Non-flooding plots from the early to the middle growth stage (36 and 57 DAT) (Fig.3-4). Significant differences in the amount of Fe^{2+} were observed for Non-flooding treatment at the middle growth stage (57 DAT) and are attributable to the water management regime (Fig 3-1).

3.3.4 Exchangeable NH_4-N Derived from Fertilizer

Exchangeable NH_4-N derived from fertilizer was present in greater amounts during the early tillering stages (20 DAT in 2011 and 24 DAT in 2012) and then, gradually decreased in amount until the maximum tillering stage (48 DAT in 2011 and 2012) and was present in intermediate amounts during the mid- tillering growth stages (29 DAT in 2011 and 36 DAT in 2012) (Fig.3-5). The NH_4-N content was the similar for all the treatments at 20 DAT and 24 DAT in 2011 and 2012, and the differences were not statistically significant. The NH_4-N at 29 DAT in 2011 and 36 DAT in 2012 were also similar for the SWD, Flooding and Non-flooding treatments. Similarly, the NH_4-N content at 48 DAT in 2011 was not significantly different for the SWD, Flooding and Non-flooding treatments. In 2012, the NH_4-N content was significantly higher for the SWD (2.0 mg kg^{-1} dry soil) treatment than for the Non-flooding (1.0 mg kg^{-1} dry soil) treatment, but the amount of

NH_4-N at this stage were negligible.

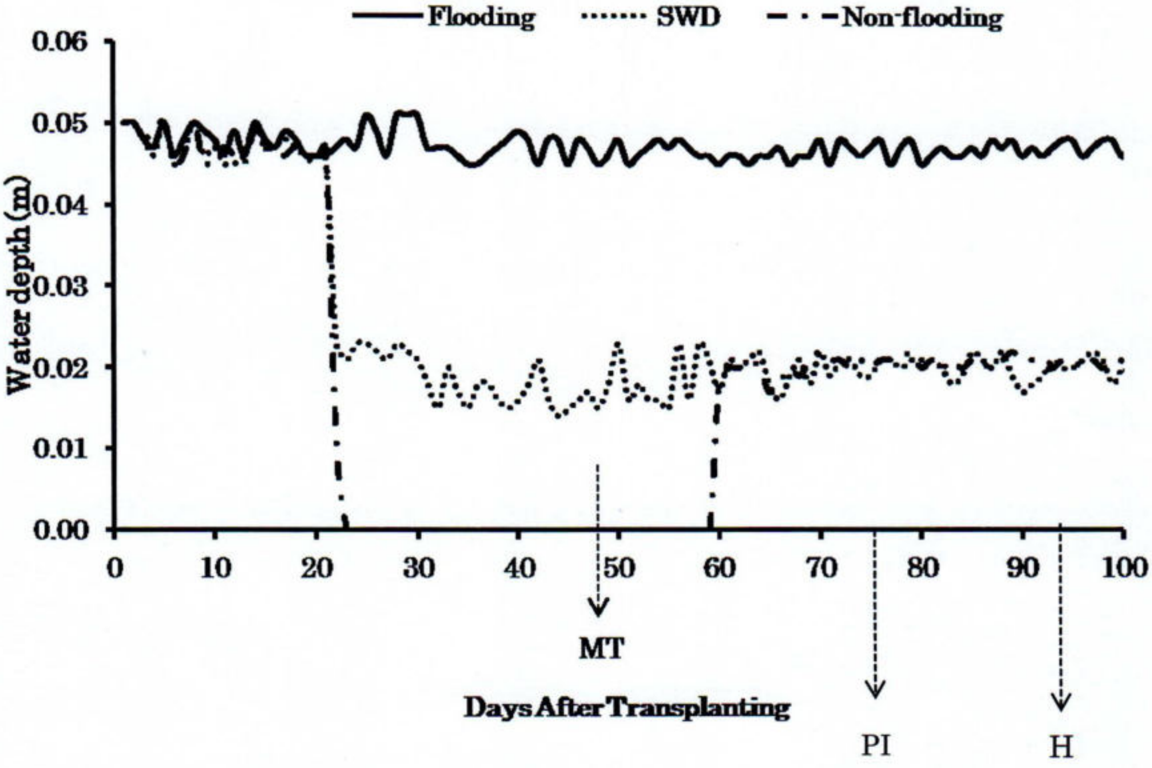


Fig.3-1. Water management in Flooding, SWD and Non-flooding water regime during rice growing period. Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded, MT: maximum tillering, PI: panicle initiation, H: heading stage

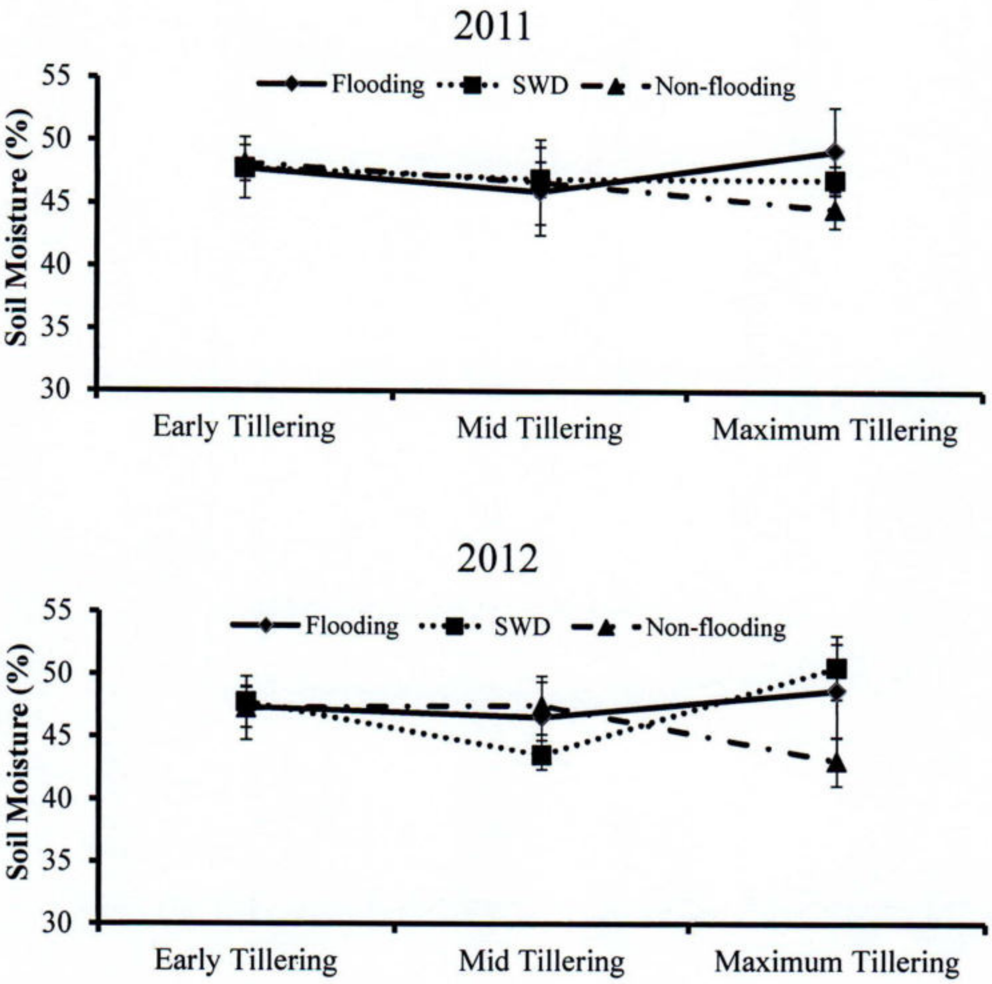


Fig.3-2. Soil moisture percentage during early to middle growth stage in the year 2011 and 2012. Vertical bar represents standard error (Tukey-Kramer test, *P* <0.05), Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded, DAT: days after transplanting

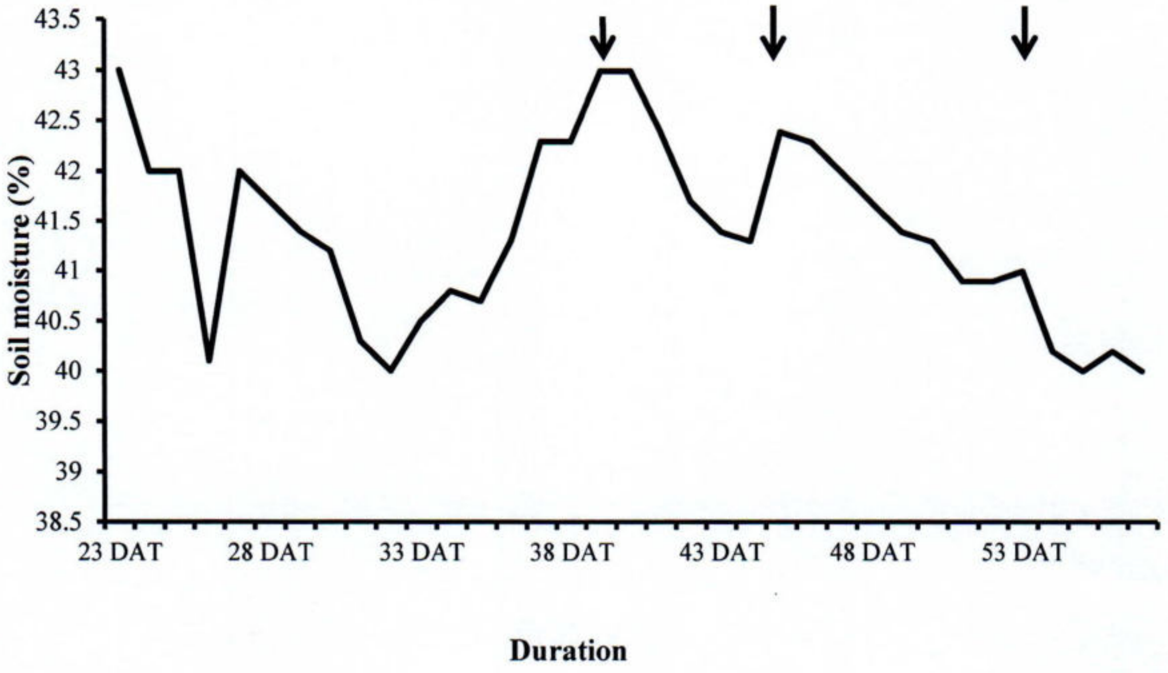


Fig.3-3. Soil moisture percentage during the Non-flooding water management period (20-57 DAT) in the year 2012. DAT: days after transplanting, → indicates irrigation time, soil moisture percentage was measured before irrigation

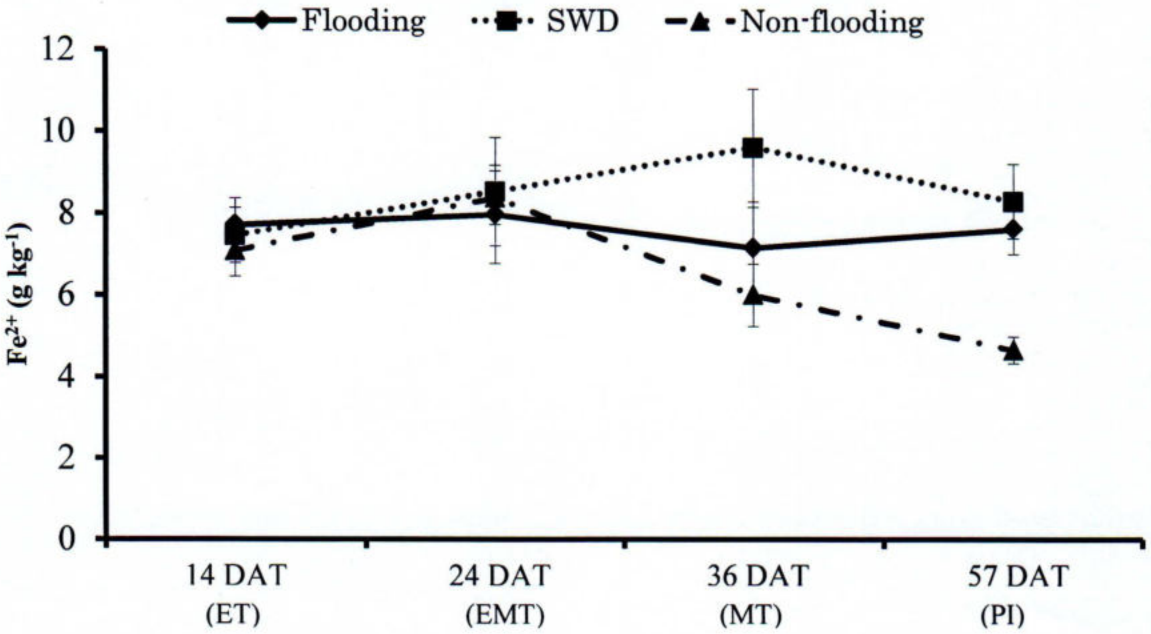


Fig.3-4. Active iron (Fe^{2+}) of soil in Flooding, SWD and Non-flooding water regime during water management period in 2012. Vertical bar represents standard error, Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded, arrow indicates start of water management at 20 DAT, ** significant $P< 0.01$ (Tukey-Kramer test, $P <0.01$), ET: early tillering, EMT: early mid-tillering, MT: mid-tillering, PI: panicle initiation stage

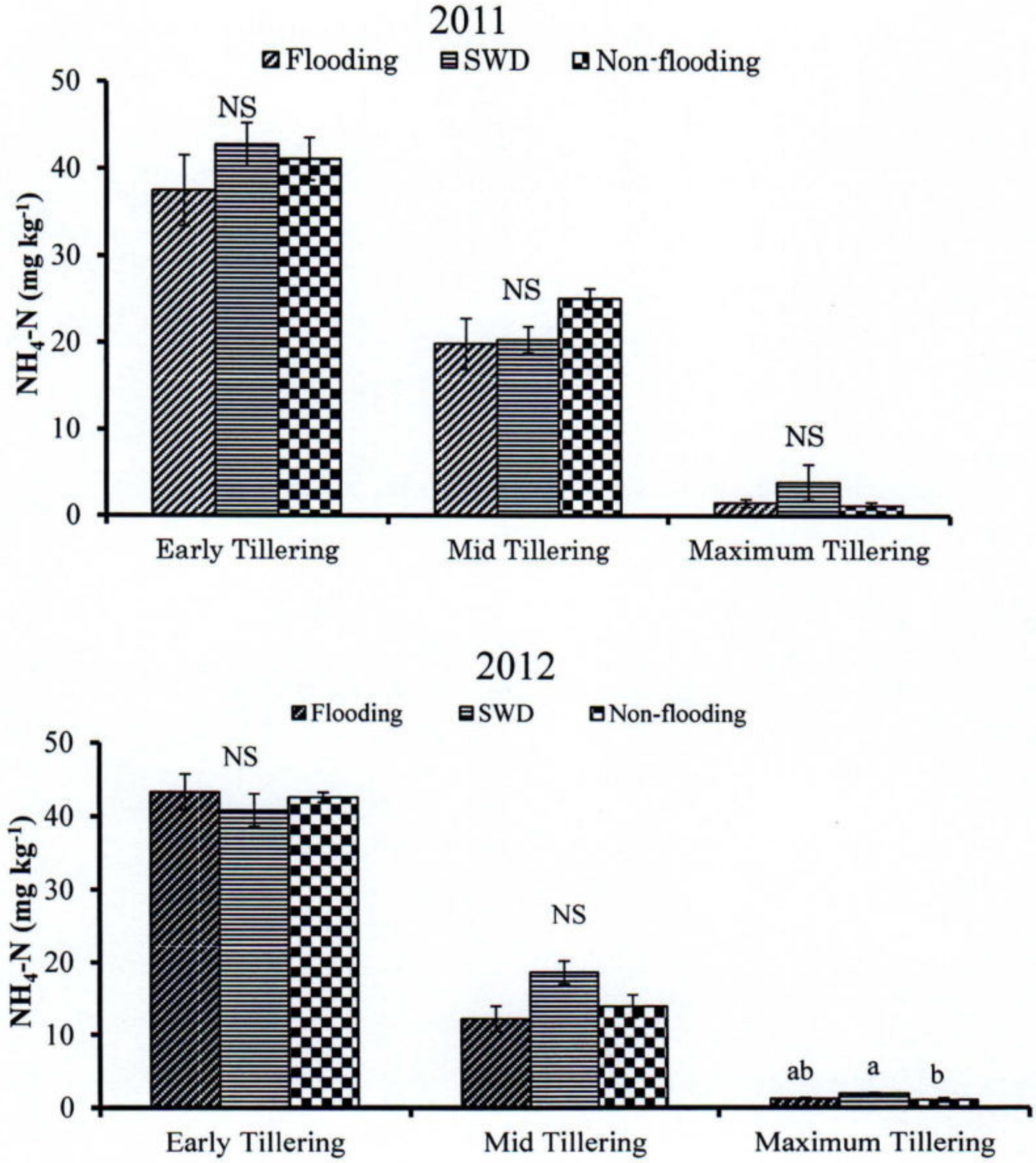


Fig.3-5. Amount of exchangeable NH_4-N derived from fertilizer in Flooding, SWD and Non-flooding water regime during early to middle growth stages of rice in 2011 and 2012. Vertical bar represents standard error, * significant at $P < 0.05$, Means followed by different lower case letter within sampling time are significantly different at $P < 0.05$, NS: non significant, (Tukey-Kramer test, $P < 0.05$), Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded, DAT: days after transplanting

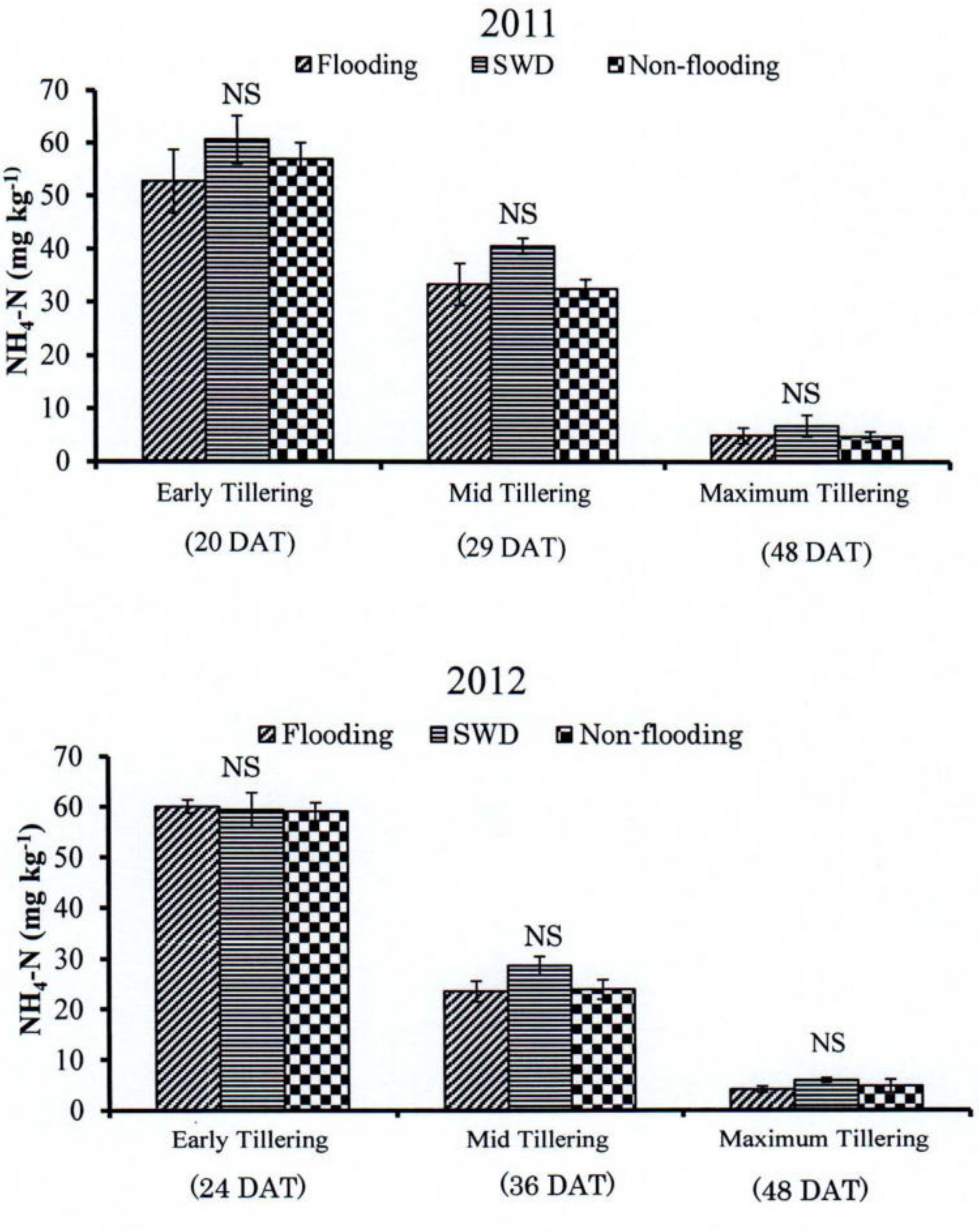


Fig.3-6. Total amount of NH$_4$-N in Flooding, SWD and Non-flooding water regime during early to middle growth stages of rice in 2011 and 2012. Vertical bar represents standard error, NS: non significant, (Tukey-Kramer test, P <0.05), Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded, DAT: days after transplanting

3.3.5 Total NH_4-N Contents

On the other hand, the total NH_4-N contents were similar for all the treatments at 20, 29 and 48 DAT in 2011 and 24, 36 and at 48 DAT in 2012, and the differences were not statistically significant (Fig. 3-6).

3.3.6 Plant Height and Tiller Number

At the maximum tillering stage, the average rice plant heights were 54.8, 55.1 and 53.4 cm for the Flooding, SWD and Non-flooding treatments, respectively, and the average heights increased to 92, 92 and 86 cm, respectively, at the heading stage. The tiller numbers m^{-2} at the maximum tillering stage were 614, 632 and 670 for the Flooding, SWD and Non-flooding plots, respectively, with 502, 532 and 528 at the heading stage. Neither the plant heights nor the tiller numbers nor the panicle numbers were significantly different at both stages (2-way ANOVA, data not shown).

3.3.7 Xylem Exudation Rate of Rice Plant

During the tillering stage (42 DAT and 39 DAT in 2011 and 2012, respectively), the xylem exudation rate varied by treatment but not by year (Table 3-2). The xylem exudation rate was significantly higher for the SWD treatment (83.9 mg $tiller^{-1}$ h^{-1}) than for the Non-flooding treatment (52.5 mg $tiller^{-1}$ h^{-1}). At the heading stage, the xylem exudation rate varied by treatment and by year but did not display interaction. Among the treatments, the SWD treatment had higher consistent xylem exudation rate (124.8 mg $tiller^{-1}$ h^{-1}) than the Non-flooding treatment (99.0 mg $tiller^{-1}$ h^{-1}) and the Flooding treatment (98.0 mg $tiller^{-1}$ h^{-1}).

3.3.8 Above-ground Biomass in Rice Plant

The biomass accumulation at maximum tillering (48 DAT in 2011 and 2012) was similar for the treatments (Table 3-3). The above-ground biomass varied by year, but the treatment and the treatment x year interactions were not significant at the maximum tillering stage. At the heading stage (80 DAT in 2011 and 79 DAT in 2012), the biomass varied by treatment, but the year and the treatment x year interactions were not significant. The above-ground biomass (950.9 g m^{-2}) in the SWD plots was significantly higher than those in the Flooding (845.5 g m^{-2}) and Non-flooding (860.7 g m^{-2}) plots. There were no significant differences in the above-ground biomass between the Flooding and Non-flooding plots.

3.3.9 N Uptake of Rice Plant

The N uptake did not vary by treatment, by year or by treatment x year interaction at the maximum tillering stage, but it did vary by treatment at the heading stage (Table 3-4). The N uptake was lowest in the Non-flooding (8.6 gm^{-2}) and Flooding (9.0 gm^{-2}) plots and highest in SWD (10.5 gm^{-2}) plots at the heading stage, and there were statistically significant differences between the SWD and Non-flooding treatments, although the differences between Flooding and Non-flooding treatments were not significant.

3.3.10 Recovery Efficiency (%) of Fertilizer N

At the maximum tillering stage, the basal recovery efficiency did not vary by treatment, by year or by treatment x year interactions (Table 3-5). At the heading stage, the recovery efficiency varied by treatment but not by year or by treatment x year interaction. Across the two years of the experiment, the SWD treatment consistently had the highest recovery efficiency (37.9%), and this recovery efficiency was significantly higher than that of the Flooding (30.5%), while the recovery efficiencies of Flooding (30.5%) and Non-flooding (32.0%) treatments were not significantly different. The top-dressing recovery efficiency varied by treatment, but the variations by year and by treatment x year interactions was not significant. Across the two years, the top-dressing recovery efficiency was higher for the SWD (54.2%) treatment than for Non-flooding (43.5%) and Flooding (45.4%) treatments.

Table 3-2 Xylem exudation rate of rice plant in the year 2011 and 2012

Source of variation	**Xylem exudation rate (mg $tiller^{-1}h^{-1}$)**	
Treatment	Tillering	Heading
Flooding	69.1ab	98.0b
SWD	83.9a	124.8a
Non-flooding	52.5b	99.0b
Year		
2011	74.8	126.5a
2012	60.1	81.6b
Significance	*P* value	
Treatment (T)	*	**
Year (Y)	NS	**
T x Y	NS	NS

*Significant at $P < 0.05$, ** Significant $P < 0.01$, Means followed by different lower case letter within a column are significantly different at $P < 0.05$ (Tukey-Kramer), NS: not significant, Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded, Tillering stage: 42 and 39 DAT in 2011 and 2012, Heading stage: 80 and 79 DAT in 2011 and 2012 respectively, each treatment 2 hills $plot^{-1}$ x 3 replication: 6 hills

Table 3-3 Above-ground biomass in rice plant in the year 2011 and 2012

Source of variation	**Above-ground biomass (g m^{-2})**	
Treatment	Maximum tillering	Heading
Flooding	216.4	845.5b
SWD	238.3	950.9a
Non-flooding	220.9	860.7b
Year		
2011	184.8b	896.3
2012	279.1a	871.5
Significance	*P* value	
Treatment (T)	NS	**
Year (Y)	**	NS
T x Y	NS	NS

** Significant $P < 0.01$, Means followed by different lower case letter within a column are significantly different at $P < 0.05$ (Tukey-Kramer), NS: not significant, Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded, Maximum tillering stage: 48 DAT in 2011 and 2012, Heading stage: 80 and 79 DAT in 2011 and 2012 respectively

3.3.11 Recovery % of LPS-100 (based on released N)

Similarly, recovery% (based on released N) was greater in SWD at maturing stage than Flooding and Non-flooding water regime. The final recovery% of LPS-100 was about 82% in LPS-100 in 2012 and 2013 under SWD water regime while 53% and 57% in Flooding and 56% and 62% in Non-flooding water regime in the year 2012 and 2013, respectively (Fig.3-7). In contrast, continuous flooding water regime did not enhance recovery% so much. The trend of recover% was smaller in Non-flooding water regime than Flooding water regime up to heading stage and after that both of them were recovered similar.

3.3.12 Yield and Yield Components of Rice

The brown rice yield varied by treatment (Table 3-6). Among the treatments and in both years, the yield obtained with SWD (6,228 kg ha^{-1}) was significantly higher (at the 1% level) than the yields obtained with the Flooding (5,774 kg ha^{-1}) and Non-flooding (5,660 kg ha^{-1}) treatments. The number of spikelets per m^2 varied by treatment, but the year and treatment x year interaction were not significant. Among the treatments and for both years, the SWD treatment yielded a significantly higher spikelet number (37,000) than the Non-flooding (32,000) and Flooding (35,000) treatments. The spikelet numbers per panicle varied by year, but the treatment and treatment x year interaction were not significant. The percentage of filled spikelets and 1,000-grain weights (g) varied by year, but the treatment x year interaction was not significant. The differences in spikelet filling (%) and 1000-grain weight between the treatments were negligible. Conversely, the panicle number per m^2 varied by treatment and by year, but the treatment x year interaction was not significant. Among the treatments for both years, the SWD treatment had the highest panicle number per m^2 (482) and the Non-flooding treatment had the lowest (431), with that for the Flooding treatment being between the two (462).

3.4 Discussion

The total water used from 20 DAT to 99 DAT for the Flooding treatment was 1.3 times higher than that for the SWD treatment and 2 times higher than that for the Non-flooding treatment. The total water use reported for conventional practices is 2 times higher than for modified SRI (system for rice intensification) irrigation in India (Satyanarayana *et al.*, 2007) and 1.4 times higher in Japan (Chapagain and Yamaji, 2010) because of the low percolation rate. It is possible that leaching losses increased with the depth of submergence during all growth stages in a paddy field as a consequence of an increased percolation rate (Magdoff and Bouldin, 1970). Stoop *et al.* (2002) reported that under controlled irrigation, intermittent irrigation was applied to keep paddy field moist and prevent standing water after the panicle initiation stage of rice, similar to the water management strategy in the rice intensification system. Similarly Mao (2002) reported that SWD is the comprehensive application of shallow water depth for the entire growing season of rice. SWD is similar to the system of rice intensification (SRI) in terms of the water management. My study which was conducted under controlled irrigation without standing water (Non-flooding) or shallow water depth (0.02 m, SWD) was same as the rice intensification system. My total water use ratio was similar to that reported in Chapagain and Yamaji (2010); the water management techniques associated with from the SWD and Non-flooding treatments decrease water consumption.

Bhuiyan and Tuong (1995) concluded that a standing depth of water throughout the season is not needed for high rice yields. They added that about 40-45 percent of the water normally used in irrigating the rice crop in the dry season was saved by applying water in small quantities only to keep the soil saturated throughout the growing season, without sacrificing rice yields. A similar result was obtained by Sato and Uphoff (2008) with the use of intermittent irrigation in SRI management. Similarly, Hatta ,1967, Tabbal *et al.*, 1992, and Singh *et al.* (1996) reported that maintaining a very thin water layer, at saturated soil condition, or alternate wetting and drying can reduce water applied to the field by about 40-70 percent compared with the traditional practice of continuous shallow submergence, without a significant yield loss. Keisuke *et al.* (2008) and Davids (1998) also reported a reduced irrigation water requirement for non-flooded rice by 20–50 percent than for flooded rice, with the difference strongly dependent on soil type, rainfall, and water management practices (Davids 1998).

Soil moisture (V/V) for all treatments and both years exhibited the same trends and no statistically significant differences in the early to maximum tillering stages. In this study, the dryness tendency was observed to be higher for the Non-flooding than for the Flooding and SWD treatments. Water-saving practices (non-flooding) will typically cause anaerobic and aerobic cycling, which are options for converting anaerobic to aerobic conditions in paddy fields (Guo and Zhou, 2007). However, my study revealed that Non-flooding did not reduce the soil moisture notably; therefore, Non-flooding treatment seems to suggest reduced conditions (Fig 2.). However, hairline cracks in the soil were observed, and the soil moisture percentage (on a weight basis) decreased to approximately 40 (data not shown). In addition, the soil moisture content for the Non-flooding treatment was lower than that for the SWD and Flooding treatments after the mid-tillering stage, although the differences were not statistically significant.

My results indicate that the amount of NH_4-N derived from fertilizer and the total amount of NH_4-N were not affected by differences in the water management treatments until 57 DAT, due to the reduced conditions of the soil. Under reduced conditions, NH_4-N is stable in soil, so loss of N also reduced.

Water management was expected to enhance aerobic soil conditions and increase the redox potential. Active or ferrous iron first appeared in the soil when the redox potential fell below 100 mV and increased in concentration with further decreases in the redox potential (Gotoh and Patrick, 1972, 1974). Non-flooding soil conditions did not properly convert Fe^{2+} to Fe^{3+} among the treatment, but Fe^{2+} was partially changed after the mid-tillering stage (36 DAT). Patrick and Jugsujinda (1992) reported the results of a study in which Fe^{2+} was changed to Fe^{3+} and NH_4-N was transferred to NO_3-N from reduced to

Table 3-4 N uptake of rice plant in the year 2011 and 2012

Source of variation	**N uptake (g m^{-2})**	
Treatment	Maximum tillering	Heading
Flooding	5.4	9.0ab
SWD	6.2	10.5a
Non-flooding	5.9	8.6b
Year		
2011	5.0	9.1
2012	7.0	9.8
Significance	*P* value	
Treatment (T)	NS	*
Year (Y)	NS	NS
T x Y	NS	NS

*Significant at $P < 0.05$, Means followed by different lower case letter within a column are significantly different at $P < 0.05$(Tukey-Kramer), NS: not significant, Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded, Maximum tillering stage: 48 DAT in 2011 and 2012, Heading stage: 80 and 79 DAT in 2011 and 2012 respectively

Table 3-5 Recovery efficiency (%) of fertilizer N in the year 2011 and 2012

Source of variation	**Recovery efficiency (%)**		
	Maximum tillering stage	Heading stage	
Treatment	Basal	Basal	Top-dressed
Flooding	35.4	30.5b	45.4b
SWD	37.9	37.9a	54.2a
Non-flooding	35.1	32.0ab	43.5b
Year			
2011	36.9	32.9	48.1
2012	35.3	33.8	47.2
Significance	*P* value		
Treatment (T)	NS	*	*
Year (Y)	NS	NS	NS
T x Y	NS	NS	NS

*Significant at $P < 0.05$, Means followed by different lower case letter within a column are significantly different at $P < 0.05$ (Tukey-Kramer), NS: not significant, Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded, Maximum tillering stage: 48 DAT in 2011 and 2012, Heading stage: 80 and 79 DAT in 2011 and 2012 respectively

Table 3-6 Yield and yield components of rice in the year 2011 and 2012

Source of variation	Panicle number	Spikelet number	Spikelet number	Filled spikelet	1000-grain wt.	Yield
Treatment	**(m^{-2})**	**($Panicle^{-1}$)**	**(10^3 m^{-2})**	**(%)**	**(g)**	**(Kg ha^{-1})**
Flooding	462ab	76	35ab	81	20.5	5774b
SWD	482a	77	37a	81	21.0	6228a
Non-flooding	431b	74	32b	86	20.9	5660b
Year						
2011	428b	78a	34	79b	21.0a	5578b
2012	510a	71b	36	88a	20.3b	6402a
Significance	*P* value					
Treatment (T)	*	NS	*	NS	NS	**
Year (Y)	**	**	NS	**	**	**
T x Y	NS	NS	NS	NS	NS	NS

*Significant at $P < 0.05$, ** Significant $P < 0.01$, Means followed by different lower case letter within a column are significantly different at $P < 0.05$ (Tukey-Kramer), NS: not significant, Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded

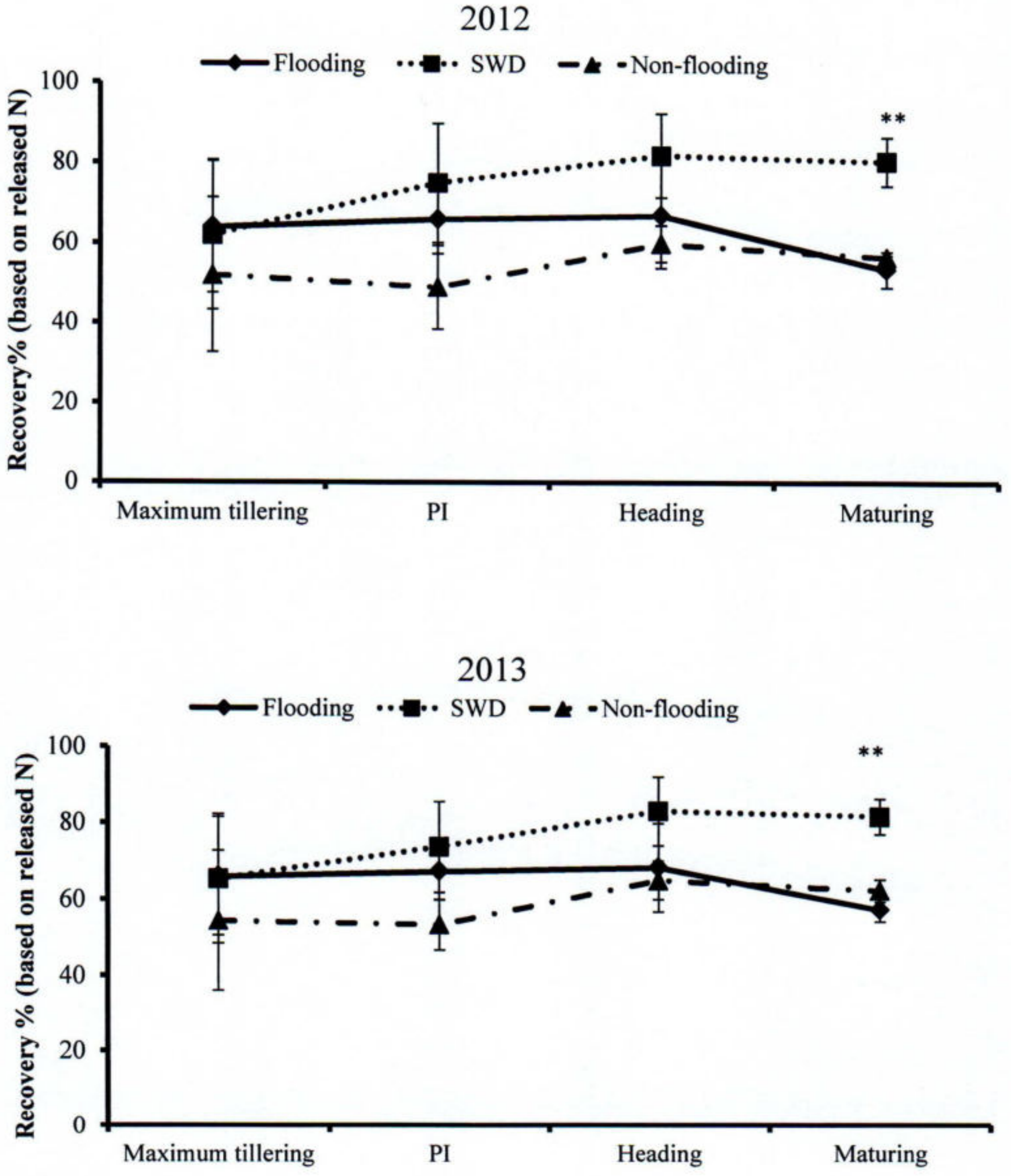


Fig.3-7. Recovery % (based on released N) pattern from slow-release fertilizer used in the year 2012 and 2013. ** Significant $P < 0.01$, (Tukey-Kramer), NS: not significant, Flooding: continuous flooded, SWD: shallow water depth, Non-flooding: kept saturated but not flooded, Maximum tillering stage: 48 DAT in 2012 and 2013, Panicle initiation stage: 59 and 60 DAT in 2012 and 2013, Heading stage: 79 and 78 DAT in 2012 and 2013, Maturing: 120 and 123 DAT in 2012 and 2013, respectively

oxidized conditions when the redox potential rose above 200 mV, and the concentrations increased further as the redox potential increased. In my experiment, no significant differences were observed in the Fe^{2+} levels among all the treatments at 36 DAT (Fig. 3), which indicates that nitrification might not have occurred largely under my soil moisture conditions. However, a significant difference in Fe^{2+} was observed at 57 DAT which suggests that nitrification might have occurred largely at 57 DAT in the Non-flooding plots but that the amount of exchangeable NH_4-N in the soil was negligible, meaning that the effect of nitrification on inorganic N was negligible.

An enhanced xylem exudation rate, which is affected by physiological activity in the root and root biomass (Yamaguchi *et al.*, 1996) during the entire growth period, especially during the heading stage, is an important phenomenon in shallow water management practices for rice plants (Table 3-2). With a constant root zone moisture content controlled under shallow water management, supplemental O_2 gas and heat (the maximum average soil temperatures were 28.8^0C, 27.3^0C and 26.8^0C for the SWD, Non-flooding and Flooding treatments, respectively) were continuously provided to the soil from 13 to 60 DAT to supply the physiological water demand, thus making the soil environment more suitable for rice root growth. Mishra *et al.* (2006) revealed and argued that this practice could be a major reason for the enhanced root activity in rice plants under shallow water management. Another report argued that one potential mechanism for enhanced root growth in warmer soils is the source-sink relationship between above-ground and below-ground plant parts. Elevated soil temperatures are known to increase the rate of photosynthesis (Day *et al.*, 1991, Schwarz *et al.*, 1997). Higher rates of photosynthesis increase the availability of fixed carbon, some of which is translocated below ground to sustain new root growth. Other possible causes of enhanced root growth with increasing soil temperatures are higher production of growth regulation substances (e.g., abscisic acid, cytokinins, gibberellins, etc.) and changes in the relative proportions these substances (Aktin *et al.*, 1973, Bowen, 1991).

No significant differences in the amount of exchangeable NH_4-N derived from fertilizer N during the tillering stage were detected among the treatments (Fig. 3-4). For both years, the basal fertilizer recovery efficiency was not significantly different among the treatments at the maximum tillering stage, and the N recovery efficiency was higher than at the heading stage (Table 3-5). Similarly, the above-ground biomass was almost the same among the treatments at the maximum tillering stage because the rice plants were able to recover the same amounts N for all the treatments. These findings indicate that the water management practices employed in this experiment did not affect the fate of the basal fertilizer N at the early growth stage. In other words, the soil did not dry enough to promote nitrification by water-saving irrigation practices under these experimental conditions. Soil conditions such as the ground-water level and the soil texture affect soil dryness in the field under different water management regimes. Different soil conditions and different water management regimes should be studied together in further research.

The N recovered from fertilizer (as a basal application) and the amounts of N in rice were significantly higher at the heading stage in both years for the SWD treatment than for the Non-flooding and Flooding treatments. The Flooding and Non-flooding treatments might have resulted in more dead leaves at the heading stage than the SWD treatment. In addition for the SWD treatment, the flag, 2nd and 3rd leaves at the heading stage were greener and more robust (data not shown) than for the Flooding and Non-flooding treatments, which indicates that the N use efficiency was reduced more by the Flooding and Non-flooding treatments than by the SWD treatment. In addition, the soil temperatures were higher for the SWD than for the other two treatments (Table 3-1).

The mechanisms for increased nutrient uptake as well as N uptake with rising soil temperature are not well understood. Root respiration is known to increase with rising soil temperature (Atkin *et al.*, 2000), in part due to higher availability of carbohydrates from enhanced photosynthesis, providing more energy for active transport. Decreased root hydraulic conductance at low root zone temperature was attributed, in part, to decreased capacity to replenish respiratory substrates in plant (Wan *et al.*, 2001).

However, the correlation between the rise in nutrient uptake and root respiration breaks down at higher temperatures, indicating that other energy-demanding processes are also changing (BassiriRad, 2000). Higher rates of root respiration result in higher concentrations of CO_2 in soil solution, of which the dissociation products, H^+ and HCO_3^- promote ion exchange reactions at the surface of clay and humic particles, freeing nutrient ions for uptake (Larcher, 1995). Formation of carbonic acid as a result of increased respiration (auto- and heterotrophic) can decrease rhizosphere and soil pH, which is widely known to affect the availability and uptake of essential ions, especially macro and micronutrients (Tisdale and Nelson, 1975; Brady, 1990; Marschner, 1995). My results also agree the above discussion and might be one of the reasons for higher N uptake and recovery efficiency in SWD than Flooding and Non-flooding treatments.
Furthermore, these soil temperatures might have increased the mineralization rate of soil organic N at later growth stages and resulted in greater amount of mineralized N for SWD. Another some report support my logic as the effect of enhanced root and microbial respiration on soil solution chemistry and plant nutrition is determined to a large extent by the buffering capacity of the soil (Wardle, 1998). At the global scale, it has long been recognized that temperature is a major controller of decomposition, resulting in the latitudinal gradient of soil organic matter (Olson, 1963). Universally, these studies have found that moderate warming of soil results in more rapid mass loss of decomposing litter, greater efflux of CO_2 from soil, and greater levels of nutrient availability (Van Cleve *et al.*, 1990; Peterjohn *et al.*, 1994; McHale *et al.*, 1998; Rustad and Fernandez, 1998).

In addition, the recovery efficiency for top-dressed N was significantly higher for the SWD treatments (Table 3-5), indicating a higher N absorption ability for rice roots in the SWD plots. More N was absorbed by rice in the SWD plots, which prolonged the photosynthetic efficiency of the lower rice leaves by keeping the xylem exudation rate of the roots high during the middle and later growth stages (Table 3-2). The results of my study suggest that different water management regimes should be examined along with rice root physiological activities and related N uptake in further research. Furthermore, recovery% of LPS-100 (based on released N) was significantly higher in SWD than Flooding and Non-flooding water regime at maturing stage. This result mentioned that LPS-100 fertilizer having releasing capacity not only uppermost layer but also the all of the Ap horizon layer because application method was same as basal N and distributed the root zone area properly during the middle rice growth. Therefore, LPS-100 fertilizer was estimated the higher root physiological activity under SWD water regime compare to other water regimes.

The releasing pattern of N in sigmoid type slow-release N fertilizer and recovery efficiency in Flooding and Non-flooding water regime was quite low at each growth stage comparing SWD water regime. The possible lower recovery% N in Non-flooding and Flooding water regime could be occurred due to lower soil temperature than SWD water regime. The soil temperature of different growth stages in Flooding and Non-flooding water regimes did not exceed 25^0C several cases. However, the actual reason of lower recovery% N was unknown. The slow-release N fertilizer releasing pattern and recovery efficiency value of my study might not be comparable to other study (Tanaka, 1990). Further research should be conducted to confirm the slow-release N fertilizer releasing pattern and their distribution.

Rice yield is mainly governed by the sink size and can be increased by increasing the sink size (Shoji *et al.*, 1986; Wada and Sta. Cruz, 1989; Yoshida, 1981). However, when the sink size is large enough, the grain yield is limited by the percentage of ripened grains to some extent (Matsushima and Tsunoda, 1958; Wada, 1969). In this experiment, significant difference in yield was observed among the treatments and SWD had the greater influenced of the yield than other two treatments. The higher yield in SWD accounts from the high fertilizer N efficiency. Thus, SWD can be conclude the following results: First was the increase in spikelet number and subsequently the spikelet per unit area is a good indicator of increase potential for grain yield with increase in spikelet numbers (Wada *et al.*, 1986). Such effect could greatly give bigger advantage in SWD due to greater panicle number per m^2, spikelet per unit area. Second was the increase N availability and recovery at critical growth stages. Generally, bigger N demand by rice fall at mid-tillering, PI and flowering stage. Such N demand is understandably rational from the viewpoint of rice nutrition and production to attain increase production of productive tiller and spikelet's per unit area, and higher filled spikelet's.

In conclusion, the SWD and Non-flooding water management can save irrigation water while the fate of N fertilizer, the N use efficiency, and the growth and yield of rice were not reduced compared to the Flooding water management.

CHAPTER 4

GENERAL DISCUSSION

4.1 Fate of inorganic N in paddy field under short/long term drainage

In paddy fields flooded condition is maintained during crop season except MSD and intermittent irrigation in Japan. Due to the water shortage, water use efficiency for rice production should be increased and one of the technologies is rice cultivation without standing water (or with shallow depth of standing water) (Belder *et al*., 2004). In the former method, soil drying conditions appears before re-flooding. The soil drying and re-flooded (DF) practice tends to result in rather dramatic change in the soil physico-chemical environment because of the transition between aerobic and anaerobic. This environment in turn controls microbial processes such as mineralization, nitrification, and denitrification that directly impact N loss and plant growth.

The nitrogen (N) uptake of the rice in DF conditions also differs from that of conventional irrigation practices due to the physiological response of rice to water stress and N availability in system of DF (Sah and Mikkelsen, 1983; Belder *et al*., 2005; Yang, 2004). In the flooded conditions, the microbial oxygen demand greatly exceeds the rate of oxygen supply to the bulk soil and the bulk of the soil is quickly reduced except oxidized top soil layer of thickness about 10 mm (Chowdary, 2004). The NO_3 -N formed in the thin oxidized layer may be taken up by the rice roots or may be diffused into the underlying reduced layer. Furthermore, NO_3 -N may be denitrified into N_2O or N_2 which readily escapes to the atmosphere (Peng, 2011). In the case of DF condition, during the aerobic period of alternate soil drying and flooding, larger part of the bulk soil would be aerobic conditions and large amounts of NH_4-N may be rapidly nitrified (Broadbent, 1971). The N losses may be increase because of nitrification–denitrification processes induced by drying and wetting cycles (Sah and Mikkelsen, 1983; Buresh *et al*., 1993). Thus, the amounts of N taken up by rice plants may be decreased under DF water management.

However, in contrast to these views, N uptake and soil exchangeable NH_4-N in the MSD, EMSD and Non-flooding treatment (Fig.2-3, 3-6) in the present study suggested that the nitrification in the DF conditions was not accelerated significantly compared with CF. Furthermore, N uptake and N recovery efficiency of rice plant in DFs were the same as the conventional (Flooding) practices (refer to Fig.2-4). If the NO_3-N is not taken up by rice plant, it is prone to denitrification losses (Reddy and Patrick, 1976) or leaching in more permeable soils (Keeney and Sahrawat, 1986). DF can lead to greater nutrient leaching than CF (Gordon *et al*., 2008). However, N leaching losses in system of DF can be reduced due to significant decrease volume of percolation water compared with CF (Peng *et al*, 2011). The interactions between water volume and N concentrations of percolation water lead the N leaching losses and N use efficiency with DF to be more uncertain and obscure. From a plant nutritional point of view, a mixer of NH_4-N or NO_3-N is better for N uptake and growth of the rice plant than the sole availability of NH_4-N or NO_3-N (Ta *et al*., 1981). Therefore is another possibility nitrification was increased in DF compared with CF and it resulted in larger N loss. But the amount of N, which is nitrified and denitrified, was negligible compared with the amounts of total exchangeable NH_4-N and total N uptake by rice plant.

My study also revealed that Non-flooding did not reduce the soil moisture notably, while hairline cracks in the soil were observed. Hairline cracks in the soil were observed in Non-flooding drainage, and the soil moisture percentage (on a weight basis) decreased to approximately 40 (refer to Fig.3-3). Therefore, Non-flooding treatment seems to suggest reduced conditions (refer to Fig.3-2). Similarly, MSD or EMSD water regime, the range of the soil moisture percentage was approximately 46 to 53 (refer to Fig.2-2) and hence, MSD or EMSD did not reduce the soil moisture compare to conventional practices (refer to Fig.2-2); thus, MSD or EMSD treatment seems to suggest reduced conditions.

My study also mentioned that, no significant differences were observed in the Fe^{2+} levels among all the treatments at Mid-tillering stage (refer to Fig.3-3), which indicates that nitrification might not have occurred largely under my soil moisture conditions. Patrick and Jugsujinda (1992) reported the results of a study in which Fe^{2+} was changed to Fe^{3+} and NH_4-N was transferred to NO_3-N from reduced to oxidized conditions when the redox potential rose above +200 mV, and the concentration increased further as the redox potential increased. However, a significant difference in Fe^{2+} was observed at panicle initiation (PI) stage which suggests that nitrification might have occurred largely at PI stage in the Non-flooding drying plots but that the amount of exchangeable NH_4-N in the soil was negligible (Fig.3-6), indicating that nitrification on inorganic N was negligible.

Non-flooding soil conditions did not properly convert Fe^{2+} to Fe^{3+} among the treatment, but Fe^{2+} was partially changed after the mid-tillering stage (refer to Fig.3-4). Non-flooding soil conditions were expected to nitrify but nitrification might not have occurred largely. Apparently the soil moisture percentage in Non-flooding water regime was approximately 40 (refer to Fig.3-2), which was lower than Conventional practices but this lower soil moisture percentage might be similar to anaerobic condition. As because the soil moisture percentage of Non-flooding was near to conventional practices and hence, Non-flooding might not convert Fe^{2+} to Fe^{3+} at all during their water regimes.

Therefore, the amount of N under DF practices, which is nitrified and denitrified, was negligible compared CF.

4.2 Soil temperature as affected by irrigation water practices

Since most chemical reactions and nutrient transport occur in water, how soil water is affected by soil temperature directly impacts nutrient uptake. It has been estimated that only 1% of the nutrients reaching the surface of plant root system is due to direct interception, while the remainder is transported to the roots by mass flow and diffusion (Jungk, 1996), although interception may be much more important for immobile nutrients such as P (Barber *et al.*, 1989). The most obvious effect of soil temperature on soil water is increased rates and depth of evaporation with decreasing soil temperature (Cortina and Vallejo, 1994; Palaez *et al.*, 1992) reported a very strong inverse relationship between soil temperature and soil water potential in rice ecosystems. This study mentioned that, lower soil temperature and higher water content and evaporation from the soil surface probably reduces soil temperature, as well soil is slower to change in temperature than controlled irrigation and drainage (Bajracharya *et al.*, 2000; Parkin and Kaspar, 2003). SWD water regime could perform as previous report. SWD water regime could affect the soil temperature on soil water was decreased rates and depth of evaporation with increasing soil temperature (refer to Fig. 3-1, Table 3-1).

Another study revealed that, after transplanting, the ponding depth is gradually increased as the height of rice increases. During the tillering periods, the ponding depth is kept shallow again to increase the soil temperature and promote the tillering (Iijima *et al.*, 1995). This study also agreed with the above statement and might be one of the reasons for warmer temperature in SWD.

4.3 Reasons for high fertilizer N recovery and N uptake under controlled irrigation

The recovery efficiency and amounts of N in rice were significantly higher at the heading stage in both years for the SWD treatment than for the Non-flooding and Flooding treatments (refer to Fig.3-4, 5). The Flooding and Non-flooding treatments might have resulted in more dead leaves at the heading stage than the SWD treatments from my observation. In addition for the SWD treatment, the flag, 2nd and 3rd leaves at the heading stage were greener and more alive (data not shown) than for the Flooding and Non-flooding treatments, which indicates that the N use efficiency was reduced more by the Flooding and Non-flooding treatments than by the SWD treatment. In contrast, the recovery efficiency and amounts of N in rice plant were not significantly higher at the days before heading (refer to Fig.2-3).

SWD could be performed well as system of rice intensification (SRI). Though SWD is a reductive soil condition but significant difference in yield was observed among the treatments and SWD had the greater influenced of the yield than other two treatments due to the higher recovery efficiency of SWD can be deduced the following reasons:

First, SWD can be better options of greater N uptake by rice plant due to higher soil temperature during entire growth period (refer to Table 3-1). Soil temperature influences plant nutrient uptake through a multitude of chemical, physical, and biological processes that interact over a wide range of spatial and temporal scales (Bonan and Cleve, 1991). When water is not limiting, nutrient availability generally increases with rising temperature due to accelerated rates of chemical reactions that liberate nutrients from primary minerals, exchange sites of clay particles, and organic matter (Clarkson *et al.*, 1988). These processes may increase nutrient availability in the SWD water regime compare to other regimes.

In addition, soil temperature has a strong influence on the community composition and activity of the soil fauna and micro flora, affecting rates of organic matter decomposition and nutrient mineralization (Carreiro and Koske, 1992). Abundance and activity of soil fauna generally increase with rising soil temperature, especially in cold soils, but can be limited by drying of the soil at high temperature. Similarly, this study mentioned that warm temperature might have increased the mineralization rate of soil organic N at later growth stages and resulted in greater amount of mineralized N for SWD (data not shown). Van Cleve *et al.* (1990) also reported the similar result as I above mentioned. Thus, rice plant uptake more N in SWD water regimes compare to Non-flooding and Flooding water regimes, as because the availability of N might be released from either fertilization or mineralization of soil organic N.

In this study also (Chapter 3) mentioned that recovery % of N (based on N released) from LPS-100 varied due to their distribution pattern of N released. If the N availability is sufficient near the root surface, then rice plant can uptake more. And then, if the N availability is continued up to maturing stage, plant can uptake more than any other climatic situation. LPS-100 could supply N slowly near the root zone and continued up to 100 days then rice plant uptake slowly and continuously during their growth period. This concept is true when water regime makes good environment for rice root. One possible mechanism for higher recovery% was SWD could enhance the root and thus rice plant can uptake much N from the root surface area. Another possible mechanism was as follows: LPS-100 is a temperature dependency fertilizer and N is released when the temperature above 25^0C. During the entire rice growth, Flooding water regime of soil temperature was obtained in between this temperature but some time slowed down and remained below the temperature. On the other hand, SWD had the higher soil temperature during the entire rice growth and hence slow-released fertilizer released much N and thus, plant can uptake easily. Therefore, slow-released fertilizer had the better distribution pattern which influences the N uptake by rice through better root physiological activities while warm temperature influences the N released under SWD water regime compare to other water regimes.

Second, the structure and function of plant root systems is in part an adaptation to variation in nutrient availability caused by the soil thermal environment. Root biomass and length generally increase with rising temperature, allowing the plant to exploit a greater volume of soil (Bowen, 1991). Root morphology, including specific root length, branching angle, and root hairs, may be directly affected by soil temperature, but experimental evidence is limited. Likewise, the effects of soil temperature on the allocation of C to the root fraction most important for nutrient uptake (Gosselin and Trudel, 1986), in the short term, specific rates of nutrient uptake increase with rising soil temperature, which may be an evolutionary response by plants to acquire nutrients that are suddenly made available. Over a period of days, however, it appears that roots acclimate to changes in soil temperature through changes in membrane fatty-acid composition and possibly transporter activity (Fitter *et al.*, 1998). Another report mentioned that, SWD practice could be enhanced root physiological activities in rice plants such as enhanced root growth in warmer soils is the source-sink relationship between above-ground and below-ground plant parts (Day *et al.*, 1991). Elevated soil temperatures are known to increase the rate of photosynthesis (Day *et al.*, 1991). Higher rates of photosynthesis increase the availability of fixed carbon, some of which is translocation below-ground to sustain new root growth (Kramer and Boyer, 1995).

4.4 Possible reasons for enhancing the root physiological activity in short/long term drainage and controlled irrigation

Root physiological activity was higher in the short/long term drainage than that in CF. As observed in this study the dryness tendency was higher in MSD and EMSD than Flooded despite soil moisture among the Flooded, MSD and EMSD treatments were same. Drainage accelerates oxygen supply to soil and it in turn might affects the root physiological activities or root mass (Stoop *et al.*, 2002)

An experiment was expected to alter the paddy field soil condition from reductive to oxidative soil condition and hence, NH_4-N convert to NO_3-N through nitrification-denitrification processes. However, my study showed different concept and not to agree the general concept as I expected. In this study, three types of drainage conducted such as MSD, EMSD and Non-flooding. EMSD is the longer drainage than MSD in 2009 and my results mentioned that both of drainage did not affect the fate of N and N uptake but could be enhanced the root physiological activities of rice (refer to Fig.2-4 and 2-5). Similarly, Non-flooding long term drainage did not affect the fate of N and N uptake of rice (refer to Fig.3-4 and 3-5).

Generally, many study have proved that more water during the early growth stage results in less aeration, less ion transport, slowing down of metabolism of root, stoppage of microbial activities and accumulation of salt in root zone and hampers the root development (Arashi, 1996). MSD or EMSD has the capabilities for reducing those factors quickly and improved the root development. In contrast, long term drainage also the potentiality to improve the soil environment but longer drainage has other difficulties for lack of microbial activities. Soil dries changes in root metabolism such as decrease in cytokinin production, an increase in ABA production. After that, disturbance of N metabolism send biochemical signals to the shoots that produce physiological changes. Thus, physiological changes decrease in growth, stomatal conductance, and rate of photosynthesis (Khalil and Grace, 1993). Such environment is not suitable for plant root and their activities hence; root physiological activities were affected less in MSD compared with Non-flooding.

The enhanced xylem exudation rate which is affected by physiological activity in the root and root biomass (Yamaguchi *et al*., 1996), thus, this study mentioned that during the entire growth period, especially heading stage, xylem exudation is an important phenomenon in shallow water management practices for rice plants (refer to Table 3-2). SWD showed higher soil temperature which continuously provide to the soil up to PI stage. It may lead the suitable soil environment for rice root growth. Furthermore, xylem exudation may be affected by root mass or physiological activity of a unit root mass. Hence, this study also revealed that root mass density was greater in SWD compare to other water regimes. Therefore, greater root mass volume influences xylem exudation rate in SWD than Non-flooding and Flooding water regimes.

Root respiration was higher in MSD than Flooded treatment at neck node differentiation stage only (refer to Fig.2-4). MSD might be due to better aeration during neck node differentiation stage. After that, root system associated with higher mobility and absorption of inorganic N in soil solution, which increased the uptake of nutrient and contributed to favorable growth attributes. Thus, better root growth in turn had resulted on higher yield attributes (Palachamy *et al*., 1989). Plant adopts osmotic adjustment at the vegetative stage which contributes the mostly noticeable mechanism of dehydration tolerance in the rice plant (Steponkus *et al*., 1980). But, any drought stress at later stages in plants which are not exposed to such drying treatment can cause great yield loss especially when plants are in the early reproductive phase (Kobata and Takami, 1981). Thus MSD in the vegetative stage may not only induce root elongation into deeper soil layers but could also help the plant to develop adaptation characteristics. Water-saving irrigation practice also improves soil characteristics, stimulates root physiological activity, tiller development and alters sink-source relationships of rice. Thus, short term drainage had the great influences on root respiration at vegetative stage due to their improved aeration soil condition compare to conventional practices.

4.5 Higher/lower yield under short/long term drainage and controlled irrigation

Short/long term drainage enhanced yield level but the difference in yield response compare to CF was not significant. Similarly, yield was not influenced by DF practices due to similar spikelet's and subsequently the same spikelet's per unit area comparing to CF (refer to Table 2-1 and Table 3-6). However, differences in yield response in EMSD20 obtained by my study and Mori and Fuji, 2007. This study revealed that there was no significant difference in brown rice yield among the three treatments in the year of 2009 and 2010. In the year 2009, the brown rice yield of MSD treatment was very low because of lodging immediately after the flowering stage. EMSD20 and MSD treatments the yield and yield components were not statistically significant compare to CF; it means prolonged drained field condition of one year data had no adverse effect on yield and yield components. Mori and Fuji, (2007) mentioned that EMSD reduces the spikelet's number than MSD under fertile soil in Shonai area. However, my research mentioned that prolonged drained (EMSD20) and also Non-flooding did not affect the growth and yield of rice (refer to Table 2-1 and Table 3-6). EMSD20 in present study did not reduce the spikelet's number compare to Mori and Fuji, 2007. One possibility for lower spikelet's number comes from either variety effect or soil moisture condition effect. If the study field was enough fertile, even dried field condition observed during the drainage stage, the spikelet's number should not be hampered. Another possibility for EMSD20 might not be dried enough during the drainage period (refer to Fig.2-2). The soil moisture percent was similar in EMSD20 and MSD than conventional practices. In contrast, yield was influenced by Non-flooding drainage due to low spikelet's number and subsequently the low spikelet per unit area comparing to SWD (refer to Table 3-6). The trend of soil moisture percent had the lower in Non-flooding drainage (refer to Fig.2-2) compare to SWD and Flooding water regimes but statistically had no differences. Therefore, soil moisture percent was same among the treatments and thus Non-flooding treatment seemed to be reduced condition. Under reduced condition, the spikelet's number was similar to CF and thus MSD, EMSD and Non-flooding drainage had the similar yield trend. Therefore, spikelet's number per unit area and filled percent spikelet's is a good indicator for higher or lower yield. Higher spikelet's number per unit area expressed as the higher yield.

4.6 Reasons for higher yield under controlled irrigation

This study showed that controlled irrigation (SWD) enhanced the yield level compare to DF and CF practices (refer to Table 3-6). There are some important factors involved which affecting the yield. The possible reasons for higher yield in SWD are as follows: First, the increase in spikelet number per unit area is a good indicator of increase potential for grain yield (Wada *et al.*, 1986). Such effect could greatly give bigger advantage in SWD due to greater panicle number per m^2, spikelet per unit area and filled percent. Higher spikelet per unit area might be influenced by root physiological activities due to their higher N absorption. Warmer temperature in soil could be one of the important factors which enhance root physiological activities visibly. Thus, warmer soil accelerates the source-sink relationship between above-ground and below-ground plants. Furthermore, elevated soil temperatures were known to increase the rate of photosynthesis, resulting in greater N absorption and thus enhancing higher number of filled spikelet's and higher spikelet's numbers, therefore, and increased spikelet's per unit area (Wada *et al.*, 1986). Therefore, this study showed higher yield in SWD compare to CF.

Second was the increase N absorption by plant and recovery efficiency of fertilizer N of paddy field at critical growth stages (refer to Table 3-4 and 3-5). Generally, bigger N demand by rice fall at mid-tillering, PI and flowering stage (Schnier *et al.*, 1990). Such N demand is from the viewpoint of rice nutrition and production to attain increase production of productive tiller and spikelet's per unit area, and higher filled spikelet's.

Thus, SWD showed higher yield compare to DF and CF practices which enhanced higher spikelet's number per unit area due to their higher root physiological activities, higher N absorption and higher recovery efficiency of fertilizer N by rice plant.

4.7 Short/long term drainage and controlled irrigation can save water or not?

The total water used for the Flooding treatment was 1.3 times higher than that for the SWD treatment and 2 times higher than that for the Non-flooding treatment during 20 to 99 DAT. Another report mentioned that, the total water use for conventional practices was 2 times higher than for modified SRI (system for rice intensification) irrigation in India (Satyanarayana *et al.*, 2007) and 1.4 times higher in Japan (Chapagain and Yamaji, 2010) because of the high percolation rate. It is possible that leaching losses increased with the depth of submergence during all growth stages in a paddy field as a consequence of an increased percolation rate (Magdoff and Bouldin, 1970). This study revealed that, the percolation rate of the Flooding (5 cm water depth) was found about 4.4 mm day^{-1} where 1.67 mm day^{-1} observed in SWD (2 cm water depths) (data not shown). The percolated rate of 1.67 mm day^{-1} in SWD was about 3 times lower than Flooded water regimes. Therefore, percolation rate is one of the important factor for reduce water in SWD. Another report mentioned that, large depth of ponded water favor high percolation rates (Sanchez, 1973; Wickham and Singh, 1978). In a field survey in the Philippines, Kampen (1980) found that percolation rates were higher for fields with deep ground water tables (>2 cm depth) than for fields with shallow groundwater tables (0.5-2 cm depth) which is similar to my study.

Bhuiyan and Tuong (1995) concluded that a standing depth of water throughout the season is not needed for high rice yields. They added that about 40-45 percent of the water normally used in irrigating the rice crop in the dry season was saved by applying water in small quantities only to keep the soil saturated throughout the growing season, without sacrificing rice yields. A similar result was obtained by Sato and Uphoff (2008) with the use of intermittent irrigation in SRI management. Similarly, Hatta (1967), Tabbal *et al.* (1992), and Singh *et al.* (1996) reported that maintaining a very thin water layer, at saturated soil condition, or alternate wetting and drying can reduce water applied to the field by about 40-70 percent compared with the traditional practice of continuous shallow submergence, without a significant yield loss. Keisuke *et al.* (2008) and Davids, (1998) also reported a reduced irrigation water requirement for non-flooded rice by 20–

50 percent than for flooded rice, with the difference strongly dependent on soil type, rainfall, and water management practices (Davids, 1998).
Thus, this study mentioned that, reduced irrigation water required for Non-flooding rice by 51% and SWD by 35% than for CF practice. Decrease water consumption was similar to that reported in Keisuke *et al.*, 2008 and Davids, 1998. Therefore, DF and SWD have the great opportunity to save water during rice growth periods.

4.8 Limitations of this study

Mid-season drainage (MSD) is one of the water-save irrigation practices and common cultural practices in Japan. MSD is short term drainage and could helpful for lodging resistance of rice and one options for reducing CH_4 emission from paddy field and also be practices for conserving water. Despite those, this study did not found any differences of soil moisture, soil NH_4-N, N uptake and yield to conventional (continuous Flooded) practices as because lack of dryness of soil due to rainfall occurred during drainage period and drying period is not sufficient to alter the soil environment.

Non-flooding is a water-saving and CH_4 mitigation technology that lowland rice can use to reduce their water consumption in irrigation field. Non-flooding water regime is seems to be long term drainage and seems to be an alternate wetting and drying during drainage period. Soil condition of paddy field could be influenced by drying and re-wetting processes. Despite those, this study also did not influenced by soil NH_4-N, N uptake, and recovery efficiency of fertilizer N, above-ground biomass and yield compare to conventional practices as because nitrification might not be occurred largely during drainage period. Non-flooding water-saving technology could be better options where water scarcity is a big issue. Carefulness should be required when establish this method. Further carefulness should be required during drainage period not to dry and take care against weed and rat attack risk.

SWD is also a water-saving and methane mitigation technology that lowland rice can use to reduce their water consumption in irrigated field. Though SWD is a reductive soil condition, SWD could be performed well as SRI. SWD water-saving technology could be better options where water scarcity and yield is a big issue. Carefulness should be required when applying organic and inorganic fertilizer. The doses of this organic and inorganic fertilizer should be ideal or appropriate. Otherwise, imbalance organic and inorganic fertilizer application affects the vigorous growth which influences lodging and finally yields level decreases.

4.9 Prospects of this study

These benefits are more relevant for the current scenario where rice production needs to be increased with reduced water application and with reduced 'climate-forcing' practices. Water-saving irrigation technique should thus be seen as an opportunity to develop more eco-friendly management practices in the rice sector.

The speculated model for fate of inorganic N and root physiological activity under DF and controlled irrigation was shown in Fig.4-1. Based on above all general discussion I can concluded that, MSD, EMSD and Non-flooding water regimes could be performed as- a) nitrification might be occurred under dried condition, but soil was not dried enough for nitrification when there were big amount of NH4-N in soil under MSD, EMSD and Non-flooding condition. Supposed to be amount of nitrified N was negligible because Non-flooding and CF had the similar N uptake and N recovery% of this study, b) root physiological activity might be influenced by DF, c) oxidized condition might be converted, but should not be largely, d) reduced condition might be continued except some changes, e) O_2 supply might be influenced by DF but not so high, f) water stress might be influenced by DF.

In contrast, controlled irrigation (SWD) could be performed as- a) O_2 supply might be influenced largely through root systems, thus, rice root physiological activity high, b) water stress might not hampered for absorbing N by rice root through the entire growth.

Therefore, water- saving cultural practices such as MSD, EMSD, Non-flooding and SWD could reduce the amount of irrigated water without reducing N uptake, growth and yield of rice plant compared to conventional irrigation management.

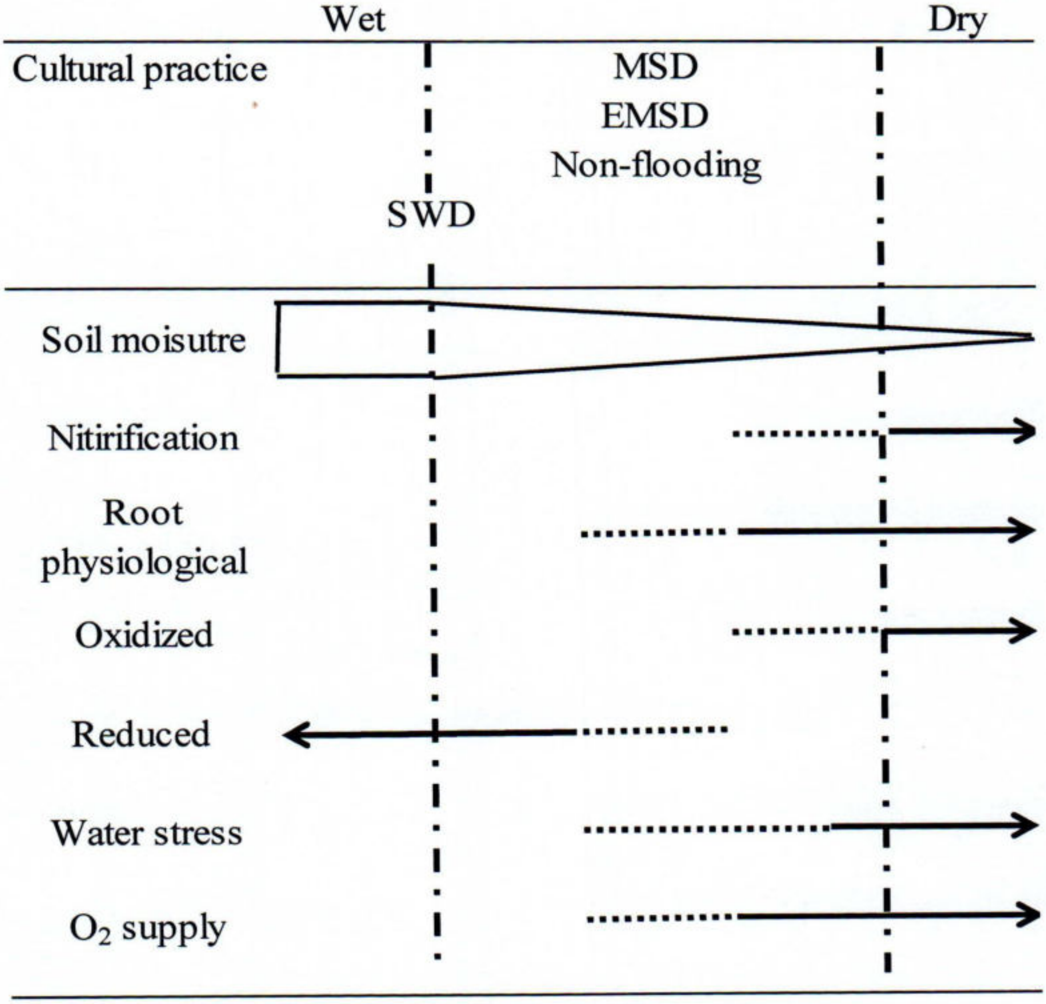


Fig.4-1. Speculate model for fate of inorganic N and root physiological activity under different water-saving irrigation practices

CHAPTER 5

GENERAL SUMMARY

Global demand for water has risen sharply over the last century. In addition, irrigated agriculture accounts for about 70 percent of freshwater withdrawals throughout the world. Increase of water scarcity will result in the decline of irrigated areas, which will further influence the agricultural production. Decreasing water availability for agriculture threatens the productivity of agricultural crops and ways must be sought to save water and increase the water productivity of agricultural crops. Many studies on water-saving irrigation managements have been conducted such as (1) mid-season drainage, (2) intermittent irrigation followed by shallow water management (3) shallow water depth. (4) alternate wet and dry periods throughout the crop cycle, (5) internal drainage, (6) continuous soil saturation and others. However, during the aerobic period of alternate flooding, NH_4-N is rapidly nitrified due to the availability of oxygen in the soil pores. Nitrification provides the substrate (NO_3-N) for denitrification when the soil is re-flooded, resulting N losses increased. On the other hands, the drying phase of rhizosphere will help root growth and its sustainability for water transport to rice plants even under low soil moisture conditions. The fate of N fertilizer, rice growth and yield under water-saving management practices is still poorly studied. Therefore, this study was conducted to examine the impacts of different irrigation practices on the N uptake and root physiological activities and to evaluate an irrigation system to save water and grain yield of rice.

In experiment I, short term drainage on root physiological activities, N uptake and yield of rice in North East Japan were compared in 2009 and 2010. In experiment II, long term drainage and controlled irrigation effect on the fate of inorganic N, growth and yield in rice were investigated in 2011, 2012 and 2013.

Experiment I

The amount of soil moisture percentage in MSD or EMSD was similar in 2009 and 2010. The dryness tendency was higher in both EMSD20 and EMSD10 than MSD and Flooded treatments in 2009 and 2010.

N uptake was higher in MSD at 41 DBH than EMSD10 and Flooded treatment in 2010 while 46 and 36 DBH was similar among the treatment. N uptake in the year 2009 at 51, 46, 41 and 31 DBH showed the similar trend among the treatment. Therefore, the trend of N uptake in plant was larger in MSD treatments during the drainage period compare to EMSD and conventional practices.

The respiration rate of rice root was significantly (5% level) higher in MSD than EMSD20 and Flooded treatment at 31 DBH in 2009. The overall trend of root respiration rate was MSD followed by EMSD20, followed by Flooded. Rice root respiration rate was same among the treatments at 38 DBH and 11 DAH in the year 2009. Similarly, respiration rate was also significantly higher in MSD than EMSD10 and Flooded treatment at 36 DBH in 2010. Other respiration rate at 24 DBH and 70 DAH stages had no difference observed among the treatment in 2010. Therefore, the trend of root respiration rate was higher in MSD than EMSD and Flooded treatments at different growth stages and thus, revealed that MSD drainage had some positive responses to respiration rate.

The xylem exudation rate was higher in MSD than EMSD and Flooded treatments during 38 DBH and 11 BAH in 2009. Similar trend of xylem exudation rate was observed in 2010 at 37, 23 DBH and 8 DAH compare to the conventional practices.

Root physiological activities in EMSD20 and EMSD10 were lower than MSD and higher than Flooded treatments.

Yield and yield components data mentioned that drained duration (EMSD20 or EMSD10), drained timing (EMSD and MSD) and drainage had no adverse effect on yield. The grain yield of EMSD20 was 594 gm^{-2} which was larger than MSD but smaller than Flooded treatment in 2009. On the other hand, the yield of EMSD10 (623 gm^{-2}) was smaller than MSD and Flooded treatments in 2010.

Experiment II

The total amounts of irrigation water used from 20 to 57 DAT in the Flooding, SWD and Non-flooding treatments were 0.87, 0.54 and 0.25 m^3m^{-2}, respectively. The total amount of irrigation water used from 57 to 99 DAT were 0.84, 0.57 and 0.58 m^3m^{-2} in the Flooding, SWD and Non-flooding treatments, respectively, and the total amounts of irrigation water used from 20 to 99 DAT, were 1.71, 1.11 and 0.83 m^3m^{-2} in the Flooding, SWD and Non-flooding treatments, respectively.

The maximum soil temperature was lower and minimum soil temperature was higher for the Flooding than for the SWD and Non-flooding treatment in 2011 and 2012.

Based on the field observations, although the differences in the soil moisture percentage between the treatments were very small, the dryness trend was higher for the Non-flooding treatments in 2011 and 2012. This study found that, the soil moisture percentage in Non-flooding treatments was approximately 40.

Active soil iron (Fe^{2+}) content was same for all the treatments at 14, 24 and 36 DAT while significance differences in the amount of Fe^{2+} was observed for Non-flooding treatment at the 57 DAT.

Total NH_4-N contents and exchangeable NH_4-N derived from fertilizer were similar for all the treatments at 20, 24 and 48 DAT in 2011 and 24, 36 DAT in 2012, and the differences were not statistically significant.

Neither the plant heights nor the tiller numbers were significantly different at maximum tillering and heading stages in the year 2011 and 2012.

The xylem exudation rate was significantly higher for the SWD treatment (83.9 mg $tiller^{-1}$ h^{-1}) than for the Non-flooding (52.5 mg $tiller^{-1}$ h^{-1}) at tillering stages in 2011 and 2012.

Similarly, SWD treatment had higher consistent xylem exudation rate (99.0 mg tiller^{-1} h^{-1}) and the Flooding treatment (98.0 mg tiller^{-1} h^{-1}) at heading stage in the year 2011 and 2012.

The above-ground biomass at maximum tillering (48 DAT in 2011 and 2012) was similar for the all treatment. The above-ground biomass (950.9 g m^{-2}) in the SWD was significantly higher than those in the Flooding (845.5 g m^{-2}) and Non-flooding (860.7 g m^{-2}) treatments at heading stage in the year 2011 and 2012.

Similarly, the N uptake at maximum tillering (48 DAT in 2011 and 2012) was similar for the all treatment. The N uptake (10.5 g m^{-2}) in the SWD was significantly higher than those in the Flooding (9.0 g m^{-2}) and Non-flooding (8.6 g m^{-2}) treatments at heading stage in the year 2011 and 2012.

Recovery efficiency of fertilizer N at maximum tillering stage did not vary by treatment while varied by treatment at heading stage in the year 2011 and 2012. SWD had the highest recovery efficiency (37.9%) than the Flooding (30.5%) and Non-flooding (32.0%) treatment, while the recovery efficiencies of Flooding (30.5%) and Non-flooding (32.0%) treatments were not significant different. Similarly, top-dressing recovery efficiency was higher for the SWD (54.2%) than for Non-flooding (43.5%) and Flooding (45.4%) treatment in the year 2011 and 2012.

The releasing pattern of N in sigmoid type slow-release N fertilizer and recovery efficiency in Flooding and Non-flooding treatment was low at each growth stage comparing SWD treatments while that value was not comparable to other studies.

In this experiment, significant difference in yield was observed among the treatments and SWD had the greater influenced of the yield than other two treatments. The yield obtained with SWD (6228 kg ha^{-1}) was significantly higher than Flooding (5774 kg ha^{-1}) and Non-flooding (5660 kg ha^{-1}) treatments. Thus, SWD can be concluding the following results:

i) An increase in spikelet's number and subsequently the spikelet's per unit area is a good indicator of increase potential for grain yield with increase in spikelet numbers.

ii) An increase in N absorption by plant and recovery efficiency of fertilizer N of paddy field at critical growth stages. Generally, bigger N demand by rice fall at mid-tillering, PI and flowering stage.

In conclusion, water-saving irrigation practices such as MSD, Non-flooding and SWD can save irrigation water while the fate of N fertilizer, N use efficiency and yield of rice were not reduced compared to the conventional irrigation practices.

要約

水資源の枯渇が世界で問題となっている。農業分野の水消費量は世界の水使用量の70%に達しているため、水資源の枯渇に伴って灌漑面積の減少、ひいては農業生産力の低下が問題となる。これを解決するため、作物の水生産効率の増加や節水栽培が研究され、水稲では、1)中干し（MSD）,2)間断灌漑、3)浅水管理（SWD）、4)乾燥と灌漑の繰り返し5)注水灌漑、6)飽水管理などが検討されている。しかし、土壌が乾燥すれば、NH_4-N窒素は硝化され、再湛水後の還元条件下で脱窒が起き窒素損失が考えられる。一方で、酸素の供給は根の活性を高めるものと考えられるが、水管理と窒素動態、水稲生育・収量に関する知見は少ない。そこで、本実験では、水田での異なる水管理条件下で窒素動態、水稲生育・収量を検討した。実験１では、MSD（慣行中干し）、および早期中干し（EMSD20（中干し開始時期が慣行より10日早く、収量は慣行と同じ、2009年試験）、EMSD10（中干し開始時が慣行より10日早く、慣行中干し開始時期に処理終了、2010年試験））について根の生理活性、窒素吸収、稲の収量を検討した。実験２では、田面水がない長期排水（ただし、田面にひび割れが入るときに再湛水、Non-flooding）とSWD（田面水深を2cmに維持）について窒素の動態、稲の生長・収量を検討した。両実験とも常時湛水区を対照とした。

実験１

MSDとEMSDの土壌水分率は2年の実験で統計的に差が認められなかったが、乾燥程度はMSD、湛水処理よりもEMSDで高い傾向が見られた。窒素吸収量はEMSD10や湛水処理よりもMSDで出穂前（DBH）41日で高かった（2010年）。しかし、46DBHと36DBHでは処理間に差が認められなかった。2009年ではいずれの時期でも窒素吸収量は処理間で差が認められなかった。

MSDの稲の根の呼吸速度は36DBH(2010年)と31DBH（2009年）にEMSD、湛水処理より有意に高かった(5%水準)。全体の傾向として、MSD、EMSD、湛

水の順に根の呼吸速度は高かった。溢液速度は同様にMSDがEMSD、湛水処理よりも高かった。また、EMSDの根の生理活性はMSDより低くいが湛水処理よりも高かい傾向が見られた。

これらのことから、排水期間(EMSD20とEMSD10)、排水時期(EMSDとMSD)は水稲の収量・収量構成要素に大きな影響を与えていないことが明らかとなった。

実験２

処理期間中（移植後（DAT）20日から57日）の灌漑水の全量は、湛水、SWD、Non-floodingでそれぞれ0.87、0.54、0.25m^3m^{-2}であった。また57DATから99DAT期間中の灌漑水量は、湛水、SWD、Non-floodingでそれぞれ0.84、0.57、0.58m^3m^{-2}であった。地温を見ると湛水ではSWDとNon-floodingよりも最高地温が低く、最低地温が高かった。処理間で土壌水分率は統計的に有意な差が認められなかったが、乾燥傾向はNon-flooding、非湛水処理において高かった。

２価鉄(Fe^{+2})含有量は57DAT以外、処理区間に差が認められなかった。57DATではNon-floodingで他の2区より有意に少なくなった。NH_4-Nがほぼ消失する時期を除いて、施肥由来NH_4-N含有量と交換性全NH_4-N含有量は処理区間に差が認められなかった。

溢液速度は分げつ期でNFよりもSWDが有意に高かったが、SWDと湛水、NFと湛水の間に有意な差が認められなかった。一方、出穂期にはSWDはNF、湛水より有意に高い溢液速度を示した。また、15Nラベル緩効性肥料を利用した生育中期の窒素吸収速度でSWDは他の2区より有意に高い利用率を示した。

生育を示す草丈、茎数も最高分げつ期と出穂期で処理区間に差は認められなかった。地上部バイオマスも最高分げつ期は全ての処理区で差が認められなかったが、出穂期のSWD　(950.9gm^{-2})で湛水処理(845.5gm^{-2})とNon-flooding(860.7gm^{-2})より有意に高くなった。窒素吸収量についてみると、最高分

げつ期に全ての処理区で差が認められなかったが、出穂期のSWD(10.5gm^{-2})は湛水(9.0gm^{-2})とNon-flooding(8.6gm^{-2})よりも有意に高かった。

基肥窒素の利用率は最高分げつ期では処理区によって差が認められなかったが、出穂期においては異なった。SWD(37.9%)は湛水(30.5%)やNon-flooding(32.0%)より有意に高い値を示し、湛水とNon-floodingには差が認められなかった。追肥窒素の利用率は湛水(43.5%)やNon-flooding(45.4%)よりもSWD(54.2%)で有意に高い値を示した。収量を見ると、SWD　(6228$kgha^{-1}$)は湛水処理(5774$kgha^{-1}$)やNon-flooding　(5660$kgha^{-1}$)よりも有意に高い値となった。これは、一穂粒数数の増加が単位面積当たりの粒数の増加をもたらし、収量の増加をもたらしたものと考えられる。

これらの結果、水稲の節水栽培技術であるMSD、SWD、Non-floodingは慣行栽培技術に比較して収量、窒素利用効率を下げることなく、大幅な節水を行うことが可能であることが明らかとなった。

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