# ESTIMATION OF NITROUS OXIDE EMISSION FROM RICE-WHEAT CROPPING SYSTEM OF ASSAM

**A THESIS SUBMITTED IN PART FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY**

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# ABSTRACT

Nitrous oxide ($N_2O$) is a major greenhouse gas contributing to global warming. Rain-fed rice fields are considered to be a notable source of atmospheric $N_2O$ emission. To investigate the dynamics of $N_2O$ emission and the relationship of plant and soil properties with emission of $N_2O$ in rice, a field experiment was conducted during autumn (*Ahu*) rice growing season (May-July, 2006). The five popularly grown rice varieties Luit, Disang, Kapilli, Siana and Phorma were grown in the fall season under rainfed conditions. $N_2O$ emission was measured at seven-day intervals starting from the day of transplanting for the whole crop growing season. We also measured soil parameters, e.g. soil pH, soil temperature, soil organic carbon, soil $NO^-_3$ -N, and field water level; and plant growth parameters: root-shoot dry weight, root length and leaf area. Our results show that $N_2O$ emission from the plant varieties ranged from 1.24 μg to 379.40 μg $N_2O$-N $m^{-2}$ $h^{-1}$. Seasonal $N_2O$ emission from the rice varieties ranged from 77 to 150 mg $N_2O$-N $m^{-2}$. Root dry weight, shoot dry weight, soil $NO_3^-$-N, root length, leaf area and field water showed relationships with $N_2O$ emission. Root and shoot weight, soil $NO_3^-$-N and field water were found to be the main factors influencing $N_2O$ emission. The varieties Phorma and Siana, with lower grain productivity but profuse vegetative growth, showed higher seasonal $N_2O$ emission.

Efforts were made to analyze $N_2O$ flux in relation to plant and soil factors from monsoon (*Sali*) rice. Ten popularly grown rice varieties namely Rashmisali, Bogajoha, Basmuthi, Lalkalamdani, Choimora (traditional varieties); Mahsuri, Moniram, Kushal, Gitesh and Profulla (high yielding varieties = HYV) were grown during monsoon season of July to November, 2006. The $N_2O$ emissions were measured the date of transplanting onwards at weekly interval along with soil and plant parameters. The seasonal integrated $N_2O$ emission ($E_{sif}$) from rice ranged from 121.63 mg $N_2O$-N $m^{-2}$ to 189.46 mg $N_2O$-N $m^{-2}$. Variety Gitesh emitted less $N_2O$ amongst all the rice varieties. $N_2O$ emission exhibited a significant positive correlation with leaf area, leaf number, tiller number, root dry weight, soil organic carbon and soil nitrate-N. Traditional rice varieties with profuse vegetative growth recorded higher $N_2O$ fluxes

compared to HYVs. Gitesh and Kushal having low seasonal $N_2O$ emission with higher yield potential can be recommended as low greenhouse gas emitting rice varieties.

Experiments were conducted to investigate dynamics of $N_2O$ emissions from summer (*Boro*) rice and rain-fed wheat fields from December 2006 to June 2007 and the relationship between soil and plant parameters with $N_2O$ emissions were investigated. The results indicated that $N_2O$ emissions from different wheat varieties ranged from 12 to 291 μg $N_2O$-N $m^{-2}$ $h^{-1}$ and seasonal $N_2O$ emissions ranged from 312 to 385 mg $N_2O$-N $m^{-2}$. In the rice season, emissions from different wheat varieties ranged from 11 to 154 μg $N_2O$-N $m^{-2}$ $h^{-1}$ with seasonal $N_2O$ emission of 190-216 mg $N_2O$-N $m^{-2}$. The seasonal integrated flux of $N_2O$ differed significantly among wheat and rice varieties. The wheat variety HUW 234 and rice variety Joymoti showed higher seasonal $N_2O$ emissions. In the wheat season, $N_2O$ emissions correlated with soil organic carbon (SOC), soil $NO_3^-$-N, soil temperature, shoot dry weight, and root dry weight. Among the variables assessed, soil temperature followed by SOC and soil $NO_3^-$-N were considered as the important variables influencing $N_2O$ emission. $N_2O$ emission in the rice season was significantly correlated with SOC, soil $NO_3^-$-N, soil temperature, leaf area, shoot dry weight, and root dry weight. The main driving forces influencing $N_2O$ emission in the rice season were soil $NO_3^-$-N, leaf area, and SOC.

An experiment was conducted to study the dynamics of $N_2O$ emission from wheat varieties viz., Sonalika, HUW 468, HUW 234 and DBW 14 grown during December, 2007 to April, 2008 under irrigated condition. Attempts were made to find out the relationship of $N_2O$ emission with plant physiological and soil properties. $N_2O$ fluxes from wheat varieties ranged from 40.67μg $N_2O$-N $m^{-2}$ $h^{-1}$ to 295.67μg $N_2O$-N $m^{-2}$ $h^{-1}$. Soil organic carbon, soil nitrate-N, soil temperature and leaf transpiration rate have shown significant relationship with $N_2O$ flux. The highest seasonal integrated nitrous oxide flux ($E_{sif}$) was recorded in the wheat variety HUW 234 followed by DBW 14, HUW 468 and Sonalika. The transpirational water flow may be an important mechanism regulating $N_2O$ transport and emission through wheat plants. Wheat variety Sonalika with yield potential of 31.76 q $ha^{-1}$ under irrigated ecosystem is found to be suitable for reducing $N_2O$ emission from wheat agriculture.

Nitrous oxide emission was estimated from autumn rice (*Ahu*) ecosystem with different doses of fertilizer combinations from May to August, 2008. Two rice varieties Phorma (local cultivar) and Luit (high yielding variety) were grown, with nine different fertilizer treatment combinations. Gas samples were collected at weekly interval along with plant and soil parameters starting from the day of transplanting. Nitrous oxide emission in rice varieties showed significant positive correlations with soil organic carbon, soil nitrate-N, leaf area, tiller number and root dry weight. Phorma and Luit showed higher seasonal integrated nitrous oxide emission ($E_{sif}$) of 224.05 mg $N_2O$-N $m^{-2}$ and 182.16 mg $N_2O$-N $m^{-2}$ respectively, in treatment $T_9$ (45:22:22 kg N-$P_2O_5$-$K_2O$ $ha^{-1}$ in the form of urea, single super phosphate and muriate of potash + FYM). Whereas, lowest emission was recorded when rice varieties Phorma and Luit were grown in grown in 35:18:18 kg N-$P_2O_5$-$K_2O$ $ha^{-1}$ ($T_2$) in the form of Urea, SSP, and MOP. The application of fertilizer N, $P_2O_5$, $K_2O$ @ 40: 20: 20 kg $ha^{-1}$ as Urea, SSP, MOP ($T_1$) without any organic amendment which yielded 29.03 q $ha^{-1}$ was found to be suitable for cultivation in autumn rice ecosystem.

# DECLARATION

I do hereby declare that the thesis entitled **"Estimation of Nitrous Oxide Emission from Rice-Wheat Cropping System of Assam"**, being submitted to the Department of Environmental Science, Tezpur University, is a record of original research work carried out by me. All helps received by me from various sources have been duly acknowledged. I also declare that neither this work as a whole nor a part of it has been submitted to any other University or Institute for any other degree, diploma or award.

Place : Tezpur University, Tezpur

Date : 23-11-2011

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## CERTIFICATE

This is to certify that the thesis entitled **"ESTIMATION OF NITROUS OXIDE EMISSION FROM RICE-WHEAT CROPPING SYSTEM OF ASSAM"** submitted to the School of Science & Technology, Tezpur University in part fulfillment for the award of the degree of **Doctor of Philosophy** in **Environmental Science,** is a record of research work carried out by **Ms. Boby Gogoi** under my supervision and guidance.

All help received by her from various sources have been duly acknowledged.

No part of this thesis has been submitted elsewhere for award of any other degree.

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*Place : Tezpur University, Tezpur* ***(Boby Gogoi)***

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# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF ABBREVIATIONS

| | |
|---|---|
| mm | Millimeter |
| °C | Degree Celsius |
| µg | Microgram |
| m | Meter |
| h | Hour |
| DAT | Days after transplanting |
| mg | Milligram |
| mµ | Millimicron |
| cm | Centimeter |
| % | Percentage |
| g | Gram |
| q | Quintal |
| ha | Hectare |
| kg | Kilogram |
| ml | Milliliter |
| DAS | Days after sowing |
| mmol | Millimole |
| ppm | Parts per million |
| meq. | Milliequivalent |
| Tg | Tera gram |
| PI | Panicle initiation |
| NBPAZ | North Bank Plain Agro-Climatic Zone |
| FYM | Farm yard manure |

# Chapter 1
# INTRODUCTION

# 1. INTRODUCTION

Climate change and global warming has become a major scientific and social issue of today's world. Global and regional climate patterns have changed throughout the history of our planet. Prior to the Industrial Revolution, these changes occurred due to natural causes, including variations in the Earth's orbit around the Sun, volcanic eruptions, and fluctuations in the Sun's energy. Since the late 1800s, the changes have been due more to increases in the atmospheric concentrations of carbon dioxide and other trace greenhouse gases as a result of human activities, such as fossil-fuel combustion and land-use change. Greenhouse gases absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface. These gases are transparent to incoming shortwave solar radiation but absorb outgoing longwave radiation, thereby trapping heat in the atmosphere. Each gas behaves differently in regard to its effect on global warming due to its concentration, residence time, and ability to absorb longwave radiation in the atmosphere. This property causes the greenhouse effect. It is an important natural phenomenon, which regulates temperature on Earth; otherwise the Earth would be about 33°C colder than at present. However, over the last several hundred years, humans have substantially added to the amount of greenhouse gases in the atmosphere. The added gases are enhancing the natural greenhouse effect, and very likely contributing to an increase in global average temperature and related climate changes. On average, the world has warmed by 0.74 ± 0.18 °C (1.33 ± 0.32 °F) over the last century with most of that occurring in the last three decades, as documented by instrument based observations of air temperature over land and ocean surface temperature (Lanzante et al., 2006; Arguez, 2007). The continuing increase in greenhouse gases concentration is projected to result in additional warming of the global climate by 1.1 to 6.4°C (2.0 to 11.5°F) by the end of this century (IPCC, 2007). An increase in global temperatures will in turn cause sea level rise, glacier retreat, melting of sea ice, and changes in the amount and pattern of precipitation. There may also be changes in the frequency and intensity of extreme weather events. These

changes of the climate will produce a range of practical effects, such as changes in agricultural yields and impacts on human health (Schneider et al., 2007).

The main greenhouse gases that contribute to global warming and climate change are water vapour, carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$) and ozone ($O_3$). In recent years, it has become evident that nitrous concentrations are increasing in atmosphere. The concentration of $N_2O$ in the atmosphere is reported to increase at the rate of about 0.25% per year (Houghton et al., 2001) as a result of anthropogenic activities. The global atmospheric concentration of $N_2O$ has increased from 270±7 ppbv in the pre-industrial period to 319±12 ppbv in 2005 (IPCC, 2007). The global warming potential of $N_2O$ is 298 times greater than that of carbon dioxide, and at a global level it contributes to around 8% of total greenhouse gas emissions (Rees and Ball, 2010). Once emitted, $N_2O$ remains in the atmosphere for approximately 114 years before removal, mainly by destruction in the stratosphere (IPCC, 2007). Due to its long atmospheric life-time, part of the $N_2O$ in the troposphere escapes into the stratosphere, where it takes part in ozone destructive reactions. It has been estimated that doubling the concentration in the atmosphere would result in a 10% decrease in the ozone layer which would increase the ultraviolet radiation reaching the earth by 20% (Crutzen and Ehhalt, 1977), eventually leading to an increase in the occurrence of health problems.

Emissions of $N_2O$ from agricultural soils are due to microbial processes of nitrification and denitrification. $N_2O$ production, transport and emission in soil depend on environmental factors such as aeration, temperature, moisture, supplies of available organic carbon, fertilization, soil pH, soil texture, etc. Numerous studies have shown increase in soil $N_2O$ emissions following N fertilizer application (Aulakh et al., 2001; Hou and Tsuruta, 2003; Wei et al., 2010).The magnitude of $N_2O$ emissions is influenced by the quantity of N applied, its source, and timing of application (Eichner, 1990). Nitrogen enters the crop system primarily from applied fertilizers, and exits via gaseous loss, leaching, harvesting removal and surface runoff. The high N rates applied usually have a high potential of being lost by leaching (Tomer and Burkart, 2003) and will accelerate $N_2O$ emissions from the soil through nitrification and denitrification and contribute to global warming. Besides soil factors plants also play a critical role in regulating the chemical and physical state of the atmosphere through

the exchange of biogenic greenhouse gases (Smart and Bloom, 2001) including $N_2O$. Plants-either aerenchymous (Mosier et al., 1990) or non-aerenchymous (Chang et al., 1998), can serve as conduits for $N_2O$ between the soil and atmosphere. They transpire significant quantities of $N_2O$ when its concentration in the soil solution greatly exceeds the solution equilibrium concentration with ambient $N_2O$ (Battle et al., 1996).

In recent years there has been growing research interest in assessing the role of growing plants in $N_2O$ production and emissions from agricultural systems (Chang et al., 1998; Grundmann et al., 1993; Müller, 2003). Understanding the role of plants will help show the nature and extent of $N_2O$ emissions from agricultural ecosystem, and minimize the uncertainty in global $N_2O$ budget (Zou et al., 2005c). In general, the contribution of growing plants to ecosystem $N_2O$ emissions has been supported by three lines of evidence (Zou et al., 2005c). First, plant roots facilitate $N_2O$ production in the soil. General denitrification models have elucidated that $N_2O$ production in soil is mainly controlled by the availability of nitrate, labile C compounds, and $O_2$ (Del Grosso et al., 2000), which is greatly affected by the existence of growing plants (Conrad et al., 1983). Second, some studies have been devoted toward understanding a role of plant pathway in ecosystem $N_2O$ emissions (Yu et al., 1997; Li et al., 2011). By comparing $N_2O$ emissions in chambers with and without rice plants, Mosier et al. (1990) showed that young rice plants facilitated the emission of $N_2O$. When the soil was flooded, $N_2O$ emission was predominately through the rice plants (Yan et al., 2000). Chang et al. (1998) indicated that plant serves as a conduit to transport $N_2O$ produced in soil to atmosphere. Finally, recent evidence suggests that plants can emit $N_2O$ under natural conditions, or plant $N_2O$ emissions were directly detected in some studies. It is suggested that rice plants during growing season may produce $N_2O$ itself and may also transport $N_2O$ produced in submerged soil to the atmosphere via aerenchyma (Xu et al. 2001).

Besides rice growing ecosystem, wheat growing ecosystem is also considered as an important source of $N_2O$. The result obtained by Smart and Bloom (2001) demonstrated that wheat leaves emit $N_2O$ during nitrate assimilation. Unlike rice plant, wheat plant does not possess aerenchyma to aid $N_2O$ emission through it; therefore some studies have suggested transpiration as a possible mechanism of $N_2O$ emission from wheat as $N_2O$ is quite soluble in water. Rice based cropping system is

considered as the major source of greenhouse gas emission (Minami and Neue, 1994; Banker et al., 1995; Wassmann and Aulakh, 2000), which contributes a major portion of all global emissions.

More than 90% of the world's harvested rice area is in Asia. In India, out of 44 million hectares of rice cultivated area, about 50% is irrigated lowland, 35% rainfed lowland, 3% deep water rice and 12% rainfed upland (Budhar et al., 2006). The major rice grown areas are distributed in locations from 8°N to 35°N with an elevation up to 3000 m above mean sea level and are spread over different agroecological subregions with subhumid to humid climate (Jha et al., 2002). About 21% of the world's food depends on the wheat crop, which grows on 200 million hectares of farmland worldwide. United Nations and other sources indicate that world population could grow upto about 8.5 billion by 2025 (Keyfitz, 1989) and to 11 billion by the end of the coming century (UNFPA, 1990). Therefore, to meet the demand of increasing population the global agricultural production will need to increase several times from present levels and this may contribute to increasing trend of global $N_2O$ emissions from agricultural sources primarily from rice and wheat ecosystems. Covering an area of 78,438 sq km, Assam is located in the South of the Eastern Himalayas. Popularly known as the 'land of the red river and blue hills', the state is a gateway to Northeast India. The economy of Assam is predominantly agrarian. About 99 per cent area of total land mass of the state is rural and almost 50 per cent of the total land area is used for cultivation. Here, rice is grown in three seasons as autumn, winter and summer rice. According to economic survey Assam 2008-09, total area under autumn, winter and summer rice are 3.70, 18.00 and 4.75 lakh hectares, respectively. Wheat is grown in an area of about 1.00 lakh hectare in rotation with rice. The area under rice and wheat cultivation has shown an increasing trend with advancement of agricultural technologies such as irrigation facilities and fertilizer use, consequently emission of $N_2O$ from the soil will also increase.

The attempts to study the dynamics of $N_2O$ emission from rice and wheat ecosystem in relation to plant and soil factors will be of great significance as it not only reduce the atmospheric $N_2O$ concentration but also increase fertilizer use efficiency in crop field thus contributing to sustainable crop productivity. Selecting rice and wheat varieties based on plant growth characteristics, yield potential, soil

properties and emission characteristics could provide an important mitigation option and based on these characteristics adequate management strategies can be developed to mitigate $N_2O$ emission from crop fields. Therefore, in present study, attempt is made to establish the relationship of $N_2O$ emission with plant physiological, soil and yield characteristics of rice and wheat varieties grown at different ecosystems with the following objectives.

i) To measure seasonal and temporal patterns of $N_2O$ emissions from rice and wheat ecosystems of Assam.

ii) To investigate the relationship of plant growth parameters and soil parameters with $N_2O$ emissions from rice and wheat ecosystems.

iii) Identification of suitable form and dose of nitrogenous fertilizer for reducing $N_2O$ emissions.

# Chapter 2
# REVIEW OF LITERATURE

# 2. REVIEW OF LITERATURE

Recent interest in nitrous oxide ($N_2O$) has been stimulated by concern about environmental consequences of the increased atmospheric level of $N_2O$. Nitrous oxide is primarily a biogenic gas implicated in both greenhouse effect and the catalytic destruction of ozone layer (Van Cleemput, 1994). Its contribution to greenhouse effect is more than other trace gases present in atmosphere, since it has got several absorption bands between 7.7 to 17 μM wavelength region (Ramanathan et al., 1985). In addition to its greenhouse gas properties, $N_2O$ is photo chemically active in the stratosphere. Atmospheric $N_2O$ is photolytically oxidized to NO in stratosphere where it reacts with stratospheric ozone and absorbs harmful solar ultra violet radiation (Crutzen, 1981).

Nitrous oxide is emitted from both natural and anthropogenic sources. Oceans and soils under natural vegetation are the major natural sources of $N_2O$ emission. According to IPCC (2007) anthropogenic sources are derived from agriculture, fossil fuel and biomass burning, industrial processes, such as adipic acid and nitric acid production, agricultural soil management like fertilization, application of manure to soils, drainage and cultivation of organic soils etc. Mosier et al. (1998) stated that $N_2O$ emissions from agricultural systems includes: (1) direct emissions of $N_2O$ from agricultural fields; (2) direct emissions of $N_2O$ in animal production systems and (3) indirect emission of $N_2O$ that are derived from N originated from agricultural systems. According to Groffman et al. (2002) nitrous oxide emission from agricultural sources includes direct emissions from fertilizer or manures applied to agricultural soils and indirect emissions from atmospheric nitrogen depositions, sewage and loss of nitrogen from agricultural fields through leaching and runoff. Although in general, $N_2O$ emissions are directly related to the fertilizer type, quantity, and method of application, but several other factors such as soil type, tillage operations, cropping intensity and diversity, cropping system and weather patterns also influences $N_2O$ emission from agricultural fields (Xiong et al., 2002; Kyveryga et al., 2004; Sauer et al., 2009). Oenema et al. (2005) reported that animal production systems are a major

and increasing source of $N_2O$ in agriculture. According to them five distinguished sources of $N_2O$ from animal production are dung and urine from grazing animals deposited in pastures (41%), indirect sources (27%), animal wastes in stables and storages (19%), application of animal wastes to land (10%) and burning of dung (3%).

Soils have been identified to be the dominant source of $N_2O$, contributing about 57% (9 Tg $yr^{-1}$) of the total annual global emissions, of which about 27% (2.4 Tg $yr^{-1}$) originates from agricultural soils (IPCC, 2001). Mosier (1994) have suggested variety of management options that may limit direct $N_2O$ emissions from N-fertilized soils. These are managing irrigation frequency, timing and quantity; applying N only to meet crop demand, either by multiple applications during the growing season or by using controlled release fertilizers or using nitrification inhibitors.

Several reports have showed that the aquatic ecosystems are important source of anthropogenic $N_2O$ to the atmosphere (Seitzinger and Kroeze, 1998; Cole and Caraco, 2001; Beaulieu et al., 2008). Emissions of $N_2O$ from rivers, estuaries and continental shelves may increase from 1.9 Tg N in 1990 to 4.9 Tg N in 2050 and over half of the increase is predicted to be concentrated in eastern and southern Asia, resulting in significant increases in coastal eutrophication (Kroeze and Seitzinger, 1998). Seitzinger et al. (2000) studied global distribution of $N_2O$ emissions from aquatic systems and reported that rivers, estuaries and continental shelves account for about 35% of total aquatic $N_2O$ emissions and oceanic emissions comprise the remainder. According to them over 90% of river and estuary emissions are considered anthropogenic (1.2 Tg N $y^{-1}$); only 25% of continental shelf emissions are considered anthropogenic (0.1 Tg N $y^{-1}$); oceanic emissions are considered natural. Overall, approximately one third of both aquatic and of terrestrial emissions are anthropogenic. Beaulieu et al. (2010) by using a global river network model estimated that microbial N transformations convert at least 0.68 Tg $y^{-1}$ of anthropogenic N inputs to $N_2O$ in river networks, equivalent to 10% of the global anthropogenic $N_2O$ emission rate. They reported that this estimate of stream and river $N_2O$ emissions is three times greater than estimated by the Intergovernmental Panel on Climate Change.

Prasad et al. (2003) studied trends in food production and nitrous oxide emissions from India's agricultural sector between 1961 and 2000 following IPCC 1996 revised guidelines. They suggested that total $N_2O$ emissions (direct, animal waste and indirect sources) increased ~6.1 times from ~0.048 to~0.294 Tg $N_2O$-N, over 40 years. Source-wise breakdown of emissions from 1961–2000 indicated that during 1961 most of the $N_2O$-N inputs were from crop residues (61%) and biological nitrogen fixation (25%), while during 2000 the main sources were synthetic fertilizer (~48%) and crop residues (19%). Direct emissions increased from ~0.031 to ~0.183 Tg. It is estimated that ~3.1% of global $N_2O$-N emissions comes from India. According to recent estimates, the India annual $N_2O$ emission is 253 Gg and is rising at a rate of 3.2% per year (Garg et al., 2006). It is projected that in annual budget of $N_2O$ emission agriculture activities account for more than 80%, including 60% from use of synthetic fertilizer, about 12% each from agriculture residue burning and indirect soil emissions and about 3% from manure management. Agriculture accounts for about 60% of the global anthropogenic $N_2O$ emissions and globally, agricultural $N_2O$ emissions have increased by nearly 17% from 1990 to 2005 (IPCC, 2007). Further it is projected that agriculture $N_2O$ emissions will increase by 35-60% up to 2030 due to increased nitrogen fertilizer use and increased animal manure production (FAO, 2003). In this chapter the processes of $N_2O$ production in soils and factors effecting $N_2O$ emission are reviewed.

## 2.1. Processes of $N_2O$ production in soils

Nitrous oxide is mainly produce in soil by natural processes of nitrification and denitrification (Firestone and Davidson, 1989; Baggs et al., 2003; Bateman and Baggs, 2005).Besides these two processes other biological as well as abiological reactions are possible mechanisms of $N_2O$ emission from the soil (Bremner, 1997; Kresovic et al., 2009). However, other processes contributing very little to $N_2O$ pool (Webster and Hopkins, 1996).

### 2.1.1. Nitrification

Autotrophic nitrification is an oxidative process in which ammonium ($NH_4^+$) is oxidized to nitrate ($NO_3^-$) via nitrite ($NO_2^-$). The reactions are generally mediated by two small groups of chemoautotrophic bacteria mainly belonging to the family *Nitrobacteraceae* (Belser, 1979). Chemoautotrophic nitrifying bacteria gain energy from the oxidation of reduced nitrogen compounds to fix $CO_2$ to organic carbon (Simek, 2000). According to Singh and Tyagi (2009) the groups of bacteria that transform the ammonium to nitrate are *Nitrosomonas*, *Nitrosolobus*, *Nitrosovibrio*, *Nitrosopira* and *Nitrosococcus* genus, and the overall nitrification process is controlled by ammonium and oxygen concentrations.

The oxidation process is carried out in two stages (Nicholas, 1978; Hooper and Terry, 1979).

a) Ammonium oxidation

$$NH_4^+ + 1\tfrac{1}{2}\, O_2 \rightarrow NO_2^- + 2H^+ + H_2O$$

b) Nitrite oxidation

$$NO_2^- + \tfrac{1}{2}\, O_2 \rightarrow NO_3^-$$

During oxidation of ammonium to nitrite hydroxylamine appears as the primary intermediate, followed by formation of nitroxyl (NOH), or its dimmer hyponitrite (Nicholas, 1978). During this stage of nitrification $N_2O$ is found to evolve (Hooper and Terry, 1979; Chalk and Smith, 1983). Schmidit (1982) stated that there are two possible ways in which $N_2O$ could arise. The intermediate nitroxyl (NOH) or its dimmer hyponitrite, may dismutate chemically under reduced $O_2$ tensions to $N_2O$ or the dissimilatory enzyme system, nitrite reductase, may yield $N_2O$ when $O_2$ becomes limiting and $NO_2^-$ replaces $O_2$ as an electron acceptor (Schmidit, 1982). Ding et al., 2007, determined the potentials of $N_2O$ production and nitrification of the soils using a 15N tracer technique and revealed that as much as 84–97% $N_2O$ and almost all NO were produced by nitrification. Evidences have shown that besides autotrophic bacteria some heterotrophic microorganisms are also implicated in the process of nitrification (Papen and Rennenberg, 1990; Brierley and Wood, 2001). Heterotrophic

nitrification is the oxidation of organic-N containing compounds to $NO_2^-$ and/ or $NO_3^-$ under aerobic conditions in presence of carbon substrates (Papen and Rennenberg, 1990). These nitrifiers use organic carbon as a source of energy (Robertson and Kuenen, 1990). The heterotrophic nitrification is carried out by bacteria, fungi and actinomycetes (Alexander, 1977; Focht and Verstraete, 1977). According to Papen and Rennenberg (1990) heterotrophic nitrification could account for important nitrogenous trace gas emissions from soils. Anderson et al. (1993), reported that heterotrophic nitrification might be as important a source of NO and $N_2O$ as autotrophic nitrification. They found that aerobically, *Alcaligenes faecalis*, a bacterium capable of concomitant heterotrophic nitrification and denitrification produced approximately the same amount of NO but 10-fold more $N_2O$ per cell than that of autotrophic nitrifier *Nitrosomonas europaea.* Brierley and Wood (2001) reported that heterotrophic bacteria and fungi promote nitrification in acid soils of coniferous forests in Western Europe and the bacteria of *Arthrobacter* sp. were found to be highly adapted to generate heterotrophic nitrification. Lin et al. (2005) isolated heterotrophic nitrifying bacteria and the efficiency of total nitrogen removal was found to be up to 80%. The batch test results showed that the isolated heterotrophic bacteria were able to nitrify. Heterotrophic nitrifiers are reported to be the main microbial contributors to $N_2O$ emission from acid soils (Nakajima et al., 2005). In incubation experiments they observed an increased $N_2O$ emission from soils after adding citrate, a substrate for heterotrophic nitrifiers and detected very small numbers of autotrophic ammonia oxidizers and autotrophic nitrite oxidizers.

### 2.1.2. Biological Denitrification

Biological denitrification is the process, of dessimilatory reduction of $NO_3^-$ or $NO_2^-$ to free NO and further to $N_2O$ and/or $N_2$ in anaerobic sites in the soil or sites with low oxygen pressures (Fillery, 1983; Robrtson and Kuenen, 1991). Denitrification is mostly done by heterothrophic bacteria, which use organic carbon compounds as their energy source, cell C source and electron donor (Paul and Clark, 1996). The most common and widely distributed denitrifying bacteria are

*Pseudomonas* species, which can use hydrogen, methanol, carbohydrates, organic acids, alcohols, benzoates, and other aromatic compounds for denitrification (Metcalf and Eddy, 2003). Microbial denitrification occurs when nitrate is present in anaerobic microsites, where the oxygen demand exceeds its supply, under water saturation or where the local $O_2$ demand is very elevated (FAO, 2001).

Pathway of reduction of $NO_3^-$ during denitrification process may be represented by the equation of Payne, 1981; Firestone, 1982.

$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$

Sequential actions of several enzymes including nitrate reductase, nitrite reductase, nitric oxide reductase, and nitrous oxide reductase are involved in reduction pathway (Zumft, 1997; Lu and Chandran, 2010). Nitrate reductase enzymes convert nitrate ($NO_3^-$) to nitrite ($NO_2^-$). It is a membrane-bound enzyme that generally consists of multiple subunits and contains Mo, Fe and labile sulphide groups (Firestone, 1982; Knowles, 1982). The reduction of $NO_2^-$ is in turn facilitated by the respiratory nitrite reductase. Nitric oxide (NO) gas is respired to $N_2O$ via the nitric oxide reductase, an iron enzyme (Zumft, 2005). Finally, $N_2O$ gas is reduced to dinitrogen by the copper enzyme nitrous oxide reductase. Pant (2009) indicated that due to high extra-cellular nitrate reductase and other enzymes associated with N transformations in sediments/waters, substantial amounts of $NH_4^+$ and $NO_3^-$ can be quickly lost from the systems as $N_2O$ and/or nitric oxide (NO), in turn, creating N limited conditions in estuarine systems. Meyer et al., 2008, have shown that although denitrification produced more $N_2O$, nitrification was the more important process for sediment $N_2O$ emission. Nitrous oxide originating from denitrification was produced in deeper sediment layers, and mostly consumed within the sediment, whereas $N_2O$ originating from nitrification was produced close to the sediment surface, allowing $N_2O$ to diffuse to the overlying water and the atmosphere. Bauza et al. (2002) have reported $N_2O$ production mainly through nitrification in red mangrove forests which are characterized by oxic conditions. However, Fernandes and Bharthi, (2010) reported that $N_2O$ production in the mangrove sediments was associated mainly with denitrification whereas its production through nitrification was non-detectable. Zhu et al. (2011) quantified the contributions of autotrophic nitrification, heterotrophic

nitrification, and denitrification to $N_2O$ production from the intensive vegetable fields. They observed that autotrophic nitrification, heterotrophic nitrification and denitrification accounted for 0.3–31.4%, 25.4–54.4% and 22.5–57.7% of the $N_2O$ emissions, respectively. When vegetable soils were moderately acidified (pH, 6.2 to ≥5.7), the increased $N_2O$ emissions resulted from the increase of both the gross autotrophic and heterotrophic nitrification rates and the $N_2O$ product ratio of autotrophic nitrification. However, once severe acidification occurred and salt stress increased both autotrophic and heterotrophic nitrification rates were inhibited.

### 2.1.3. Nitrifiers denitrification

Nitrifier denitrification is the pathway of nitrification in which ammonia ($NH_3$) is oxidized to nitrite ($NO_2^-$) followed by the reduction of $NO_2^-$ to nitric oxide (NO), nitrous oxide ($N_2O$) and molecular nitrogen (Wrage et al., 2001). The transformations are carried out by autotrophic nitrifiers. Thus, nitrifier denitrification differs from coupled nitrification–denitrification, where denitrifiers reduce $NO_2^-$ or nitrate ($NO_3^-$) that was produced by nitrifiers (Wrage et al., 2001). Studies have suggested that nitrifiers denitrification may contribute significantly to $N_2O$ production in soil (Webster and Hopkins, 1996; McLain and Martens, 2005; Venterea, 2007). Shaw et al. (2006) reported that *Nitrosospira* spp. which is dominant ammonia oxidizing bacteria (AOB) in soil can produce nitrous oxide via a nitrifier denitrification pathway. They found that all AOB tested were able to carry out nitrifier denitrification under aerobic conditions, as determined by production of $^{15}N$-$N_2O$ from applied $^{15}N$-$NO_2^-$. Their results suggested that nitrifier denitrification could be a universal trait in the beta-proteobacterial ammonium oxidizers. Kool et al. (2010) proved that nitrifier denitrification occurs in soils by using a new isotopic approach. They observed that $N_2O$ production in most of soils is contributed by nitrifier denitrification. Moreover, it may even have been responsible for all $NH_4^+$-derived $N_2O$ in most soils. Kool et al. (2011) suggested Nitrifier denitrification as a distinct and significant source of nitrous oxide from soil. They showed that when moisture conditions are sub-optimal for

denitrification, nitrifier denitrification can be a major contributor to $N_2O$ emission from poor sandy soil.

### 2.1.4. Chemodenitrification

Chemodenitrification is the production of nitric oxide (NO) and $N_2O$ from the chemical decomposition of nitrite (Morkved et al., 2007). It generally occurs when $NO_2^-$ accumulates and reacts with organic compounds to produce NO and $N_2O$ (Bremner, 1997). It is reported that chemodenitrification is closely linked with nitrification and it is often difficult to determine whether $N_2O$ is developed through nitrification or chemodenitrification (Martikainen and De Boer, 1993). However, Morkved et al. (2007) observed that chemodenitrification can contribute significantly to the apparent nitrification-derived $N_2O$ emissions. They reported that for the soils with pH 4.1 and 4.2, the apparent $N_2O$ product ratio of nitrification was 2 orders of magnitude higher than above pH 5. This could partly be accounted for by the rates of chemodenitrification of $NO_2^-$. Kresovic et al. (2009) showed that decelerated chemoautotrophic nitrification was the source of the occurrence of nitrite in the examined less acid soil, while in soils of higher acidity after addition of 100 and 300 ppm $NH_4$–N, nitrite occurred due to chemical denitrification (chemodenitrification). They observed that nitrites formed in the process of chemodenitrification underwent spontaneous chemical oxidation resulting in nitrate formation through chemical nitrification.

## 2.2. Factors affecting the emission of nitrous oxide

### 2.2.1. Soil water and aeration

Oxygen availability is the dominant factor limiting denitrification in aerobic systems (Tiedje, 1988). Anderson and Levine (1986) investigated the effect of partial

pressure of oxygen on the production of $N_2O$ by soil nitrifying, denitrifying and nitrate-respiring bacteria under laboratory conditions and found that $N_2O$ production was inversely proportional to oxygen partial pressure. According to Davidson (1991) high soil water content increases $N_2O$ emission rates, as a consequence of limited oxygen diffusion through soil pores. Values of 40% of the Water Filled Pore Space (WFPS) are commonly considered the lower limit to obtain measurable fluxes in non-limiting conditions of N and C sources (Davidson, 1991). Linn and Doran (1984) reported that nitrification rates increases with soil moisture up to 60% water-filled pore space (WFPS). As WFPS exceeds 60%, availability of $O_2$ and $CO_2$ substrate for nitrifiers declines due to severely restricted diffusion rates (Davidson and Schimel, 1995). Denitrification generally occurs when the soil water content is high enough to restrict the supply of $O_2$ via diffusion (Hutchinson and Davidson, 1993). Thus, denitrification is usually associated with soil water content above 60 % WFPS (Davidson, 1991). It has been reported that maximum $N_2O$ is produced when $O_2$ concentrations are low enough to promote reduction of $NO_3$, but not so low as to promote reduction of $N_2O$ to $N_2$ as $O_2$ is known to inhibit nitrous oxide reductase (Davidson and Schimel, 1995). This is the reason that flooded soils contribute less $N_2O$ to the atmosphere than aerobic soils.

Kumar et al. (2000) reported that continuous submergence in rice crop would reduce nitrification and accumulation of $NO_3^-$, thereby reducing $N_2O$ production whereas, in other crops, when stagnation of water is avoided and crops are grown in aerobic or partially aerobic conditions, $N_2O$ emission may be higher mainly due to high nitrification and to some extent, via denitrification of accumulated $NO_3^-$ in periods of water saturation. It is well documented that midseason drainage in rice paddies triggers substantial $N_2O$ emission in contrast with continuous flooding (Cai et al., 1997; Zheng et al., 2000). Moreover, $N_2O$ fluxes during intermittent irrigation periods depend strongly on whether or not water logging is present in paddy fields, which often begets a significant difference in seasonal total of $N_2O$ emissions between the water regimes of flooding-midseason drainage- reflooding and flooding-midseason drainage- reflooding-moist intermediate irrigation but without water logging (Zou et al., 2005a). Pathak et al. (2005) observed that in Indian rice fields continuous flooding resulted in annual net emissions of 1.07–1.10, 0.04–0.05 and

21.16–60.96 Tg of $CH_4$-C, $N_2O$-N and $CO_2$-C, respectively, with a cumulated global warming potential (GWP) of 130.93–272.83 Tg $CO_2$ equivalent. Intermittent flooding of rice fields reduced annual net emissions to 0.12–0.13 Tg $CH_4$-C and 16.66–48.80 Tg $CO_2$-C while $N_2O$ emission increased to 0.05–0.06 Tg $N_2O$-N. It is reported that in fertilized paddy fields $N_2O$ emission considerably increased with midseason drainage compared to continuous flooding (Akiyama et al., 2005; Zou et al., 2007). Water regime is reported to influence the availability of nitrogen, labile C compounds and $O_2$ in paddy soils that are key factors to $N_2O$ production in general denitrification models (Firestone and Davidson, 1989).

Zou et al. (2007) reported that the midseason drainage and dry-wet alteration are able to improve root activities and accelerate soil organic C decomposition, which might produce more available C and N for soil microbes and thereby favor $N_2O$ emission Machefert and Dise (2004) observed an exponential relationship between denitrification rates and soil moisture, with sharp increase at water- filled pore space of 60-80% in a riparian ecosystem. Schindlbacher et al. (2004) also showed that $N_2O$ emissions increased with increasing water filled pore space (WFPS) or decreasing water tension, respectively. Maximum $N_2O$ emissions were measured between 80 and 95% WFPS or 0 kPa water tensions. Singurindy et al. (2009) found that increasing soil saturation in a wet area formed during a spring thaw caused increasing $N_2O$ emissions up to a maximum of 200 $\mu g\ Nm^{-2}\ h^{-1}$ at ~60–70% saturation. However, emissions dropped dramatically with further increases in soil moisture, decreasing to 50 $\mu g\ Nm^{-2}\ h^{-1}$ in the most saturated areas. Loecke and Robertson (2009) observed significant influence of soil moisture on litter aggregation stimulated $N_2O$ emissions from agricultural soils. They observed that in moist soil at 50% water filled pore space, litter aggregation delayed the peak litter decomposition rate by 3–5 days compared to uniformly distributed litter regardless of the litter particle size. In contrast, under near-saturated soil conditions (80% water filled pore space) litter aggregation suppressed decomposition throughout the 26-day incubation period. Further higher $N_2O$ emissions were observed at 50% water filled pore space. This interaction between litter aggregation, decomposition and soil moisture is influenced by $O_2$ diffusion. Song et al. (2010) investigated the responses of in situ denitrification rates, denitrifying bacterial community structure and their quantities using nitrite reductase

(nir) S gene under different hydrological pulsing conditions in created wetlands in central Ohio USA. Average denitrification rates, measured from 4 different sampling locations, were 302, 133, 71 and 271 mg $N_2O$-$Nm^{-2}$ $h^{-1}$ during inundated, saturated, drying and reflooding periods, respectively. Rafique et al. (2011) studied $N_2O$ emission from grassland soils and found that at below 40% WFPS, $N_2O$ production was less than 35 μg $m^{-2}$ $h^{-1}$ but increased to 122 μg $m^{-2}$ $h^{-1}$ at 60% WFPS. Peak emissions occurred in the range of 60–80% WFPS with maximum emission at approximately 70% WFPS. The most probable explanation of the peak $N_2O$ emission between 60 and 80% WFPS is that emission increased to a level where simultaneous denitrification and nitrification were at their maximum (70% WFPS). Above this WFPS, denitrification was the main process producing $N_2O$ and as the soil is more anaerobic. Similar response was also reported by Arriaga et al. (2010). Ranucci et al. (2011) monitored soil $N_2O$ emissions throughout a 3-year crop rotation including maize, fennel and a ryegrass-clover sward, and observed that $N_2O$ emission rates were highly variable in time and space and found that irrigation regime was key determinant in $N_2O$ seasonal budgets.

### 2.2.2 Carbon availability

The availability of organic C is an important factor regulating the denitrification process in the soil (Beauchamp et al., 1989). According to Burford and Bremner (1975), the rates of denitrification are usually correlated positively to water soluble or easily decomposable organic carbon. This is because the denitrifying bacteria prefer the easily decomposable organic matter as their energy source, cell C source and electron donor (Tiedje, 1988). Several studies have shown that the addition of nitrate and labile C to soils increases the rates of denitrification from various ecosystems (Ashby et al., 1998; Mohn et al., 2000; Laverman et al., 2001; Wallenstein et al., 2006; Chatterjee et al., 2008; Inagaki et al., 2008; Perez et al., 2010). The magnitude of emissions varies depending on residue composition or quality and quantity of biomass incorporated (Aulakh et al., 1991; Ambus et al., 2001; Baggs et al., 2001; Millar and Baggs, 2004). Huang et al. (2004) observed that incorporation of

plant residues enhanced $N_2O$ emissions and the cumulative emissions of $N_2O$ were negatively correlated with the C:N ratio in plant residues while positively correlated with dissolved organic carbon (DOC) concentration measured at the end of the incubation. They suggested that the residues with lower C:N decomposed more and might have provided a greater opportunity for producing more DOC, hence resulting in higher $N_2O$ emissions. Whereas, the residues with higher C:N ratio presumably stimulated $NH_4^+$ immobilization and $N_2O$ consumption through its reduction to $N_2$ and hence reduced $N_2O$ production. Similar observations of reduction in $N_2O$ emission with increased C:N were reported by (Bremner and Blacker, 1981; Flessa and Beese, 1995; Ellis et al., 1996; Zou et al., 2004). Klemedtsson et al. (2005) found a strong negative relationship between $N_2O$ emissions and soil C:N ratios in forested histosols in Sweden.

Studies have reported that the amount of DOC is a measure of the readily available resource for microbial growth and biological decomposition and is often being considered as a good index of C availability (Zack et al., 1990; Liang et al., 1996; Jensen et al., 1997). The release of organic C from plant roots is one of the important sources for C accumulation, transformation and emission from soils (Lu et al., 2000). They suggested that DOC pool in the root zone of rice plants is enriched by root-derived C and the intercultivar difference in root C releases is responsible for the intercultivar difference in DOC production, and consequently gas emission. Harrison and Matson (2003) observed that average per-area $N_2O$ flux in both purely agricultural and mixed urban/agricultural drainage systems was high compared to other fresh water fluxes, and extreme values ranged up to 244.6 ng $N_2O$-N $cm^{-2}$ $hr^{-1}$. They reported that extremely high $N_2O$ fluxes occurred during green algae blooms, when organic carbon, nitrogen, and oxygen concentrations were high, and only in canals receiving pig-farm and urban inputs. In a laboratory experiment, Sehy et al. (2004) attempted to simulate freeze-thaw related $N_2O$ emissions from soil by adding dissolved organic C (DOC) to soil of high water content. The addition of DOC to unfrozen soil resulted in a substantial (22-fold) increase in $N_2O$ emissions as compared to the control. However, following thawing, the increase in $N_2O$ emissions was much larger. By adding $^{15}N$-labeled nitrate to the soil samples, they identified denitrification as the main process leading to elevated $N_2O$ flux rates after both DOC

addition and freeze-thaw treatment and concluded that the availability of C substrate plays an important role for freeze-thaw-related $N_2O$ emissions.

Fernandez et al. (2007) observed that the addition of organic fertilizers significantly increased the proportion of $N_2O$ from denitrification in relation with control plots. They suggested that this effect could be due increased DOC content of the soil increasing with the addition of organic fertilizers. Bhandral et al. (2010) observed that nitrous oxide emission from grazed dairy pasture was enhanced following application of farm dairy effluent which was due farm dairy effluent added soluble carbon to the soil. Based on the analysis of sensitivity tests Wang et al., 2011 observed that dissolved organic carbon (DOC) is the only energy source for the entire denitrogenation process. According to them higher SOC have generated more DOC, which in turn increased denitrification until the final product $N_2$ is produced. Further they also observed that increased manure amendment from 2000 to 4000 kg C $ha^{-1}$ $yr^{-1}$ increased annual $N_2O$ emission rates from 4.51 to 5.42 kg N $ha^{-1}$ $yr^{-1}$.

### 2.2.3. Temperature

Temperature plays a significant role in the process of $N_2O$ emission. The optimum temperature for $N_2O$ production is reported to range from 25 to 40°C (Granli and Bockman, 1994). It is reported that soil temperatures less than 5°C are generally inhibitive to nitrifier activity (Anderson and Boswell, 1964). Denitrification has been observed at temperatures near freezing and as high as 70°C (Holtan-Hartwig et al., 2001). In temperate climate seasonal and diurnal changes in soil temperature have been shown to be correlated, directly and linearly, with $N_2O$ emission (Skiba et al., 1998; Skiba and Smith, 2000). But this is only true when other important factors such as water filled pore space (WFPS) or mineral N are not limiting. According to (Dobbie and Smith, 2003) relatively high $N_2O$ emissions were only observed when soil WFPS, temperature and $NO_3$ –N concentration values were higher than 65%, 4.5°C and 5 mg $kg^{-1}$, respectively. Investigations have showed that soil $N_2O$ emissions are enhanced by temperature, whereas at low temperature other factors, such as soil N availability and water content, play a controlling role (Conen et al.,

2000; Sehy et al., 2003; Lee et al., 2008). Saggar et al. (2004) have reported an increase in $N_2O$ emissions from dairy grazed pastures by increasing temperature from 5°C to 18°C. While evaluating the effect of crop residue application and temperature on $CO_2$, $CH_4$, and $N_2O$ emissions within an entire rice-wheat rotation season, Zou et al. (2004) observed an exponential relationship between air temperature and the $N_2O$ emissions from the non waterlogged period of the rice-growing season. This relationship yields a Q10 value of 3.9±0.4, which was comparable to the Q10 value for the heterotrophic $N_2O$ production rates over the temperature ranges from 25°C to 40°C (Castaldi, 2000).

$N_2O$ emissions have been reported to decrease with repeated freeze–thaw cycles (Schimel and Clein, 1996; Prieme and Christensen, 2001). The decrease in gas production suggests either depletion in microbial nutrient availability or damage to soil microbes. Several studies have reported significant $N_2O$ losses from cultivated soils following freeze–thaw cycles in spring (Nyborg et al., 1997; Wagner-Riddle and Thurtell, 1998). Kaiser et al. (1998) suggested that $N_2O$ emissions during the time of deepest soil freezing occurred as a result of $N_2O$ production in deeper soil horizons, with the gas escaping through frost-induced cracks. Teepe et al. (2001) observed constant $N_2O$ emission for several days in freezing periods as evidence of microbial activity in the frozen soil. Significant positive correlations between $N_2O$ emission factor and mean annual air temperature are reported by Toma et al. (2007) and suggested that $N_2O$ emission derived from chemical nitrogen fertilizer increases as air temperature rises. Singurindy et al. (2009) found that the emission of $N_2O$ from manure-amended soils was not limited to thawing events. The emissions began at soil temperatures below 0°C and continued even after complete soil freezing. Overall, maximal emissions were found at temperatures greater than 5°C and at water filled porosities between 40 and 70%. According to them during the period from 41 to 65 days after manure application, considerable snow precipitation caused the formation of the deep snow and ice layer that prevented the escape of nitrous oxide. During the subsequent thaw, the trapped $N_2O$ was released within few days, resulting in a high $N_2O$ emission peak.

Neto et al. (2011) studied $N_2O$ emissions from soils of tropical forests and suggested that increased air and soil temperatures may result in high decomposition

rates and gross inorganic nitrogen fluxes that could support consequent increases in soil $N_2O$ and $CO_2$ emissions and soil $CH_4$ consumption. While studying gas exchange in a gradient of elevation in the coastal Brazilian Atlantic forest soil Rafique et al. (2011) observed increase in $N_2O$ emissions from 20 $\mu g\ m^{-2}\ h^{-1}$ to 110 $\mu g\ m^{-2}\ h^{-1}$ when temperature increased from 5°C to 17°C. According to them the $N_2O$ emission is assumed to be dominated by biological activities as increased temperature enhances microbial activity (Scanlon and Kiely, 2003).

### 2.2.4. Soil pH

In pure cultures and in soils, the rate of denitrification is found to be positively related to pH and the optimum pH for denitrification was reported in the range of 7.0 to 8.0 (Van Cleemput and Patrik, 1974; Muller et al., 1980). The denitrification rates increases with increasing soil pH (Tate, 1995) and can be strongly inhibited at soil pH below 6.0 (Klemedtsson et al., 1978; Muller et al., 1980). Studies have showed increasing $N_2O$: $N_2$ when pH declines this is because of high sensitivity of $N_2O$ reductase to low pH than the other denitrification reductases (Blackmer and Bremner, 1978; Firestone et al., 1980; Nagele and Conrad, 1990; Thomsen et al., 1994; Simek and Cooper, 2002; Dannenmann et al., 2008; Cuhel et al., 2010).

Investigations have showed that nitrification can occur in soil of pH 4 to 5 (Matson and Vitousek, 1981; Vitousek et al., 1982; Olson and Reiners, 1983). According to Goodroad and Keeney (1984) the nitrification of $NH_4^+$ fertilizers increased with increasing pH from 4.7 to 6.7. While studying $N_2O$ emissions from acidic tea field soil of Japan a negative exponential relationship between the soil pH value and $N_2O$ emission potential was observed (Tokuda and Hayatsum, 2001). Feng et al. (2003) in an incubation study observed that during denitrification, cumulative $N_2O$ emissions enhance by increasing soil pH and reached much higher values of 1600 $\mu g\ N\ kg^{-1}$ in comparison to 40 $\mu g\ N\ kg^{-1}$ under nitrification conditions. They found that under alkaline conditions at pH 8.1, a large nitrite accumulation occurred, due to high nitrate reductase activity. At pH 6.7 the total $N_2O$ emission was slightly higher than at pH 8.1, although the start of pronounced emissions was retarded and

only small amounts of $NO_2^-$ accumulated. Whereas at pH 5.2 and 4.4 $N_2O$ emission was small or negligible. Their results concluded that acidic mineral soil, used alternatively for production of upland crops or paddy rice, are prone to high $N_2O$ emissions after flooding, particularly under neutral to alkaline conditions. Therefore, in order to avoid major $N_2O$ evolution and accumulation of nitrite, which can be leached into groundwater, the pH should not be raised to values above 5.5–6 while liming. Kyveryga et al. (2004) observed significant relationships between soil pH and percentage nitrification of fall applied anhydrous ammonia. Means of measurements made in mid-April (when planting begins) indicated 89% nitrification of fertilizer N in soils having pH >7.5 and 39% nitrification of this N in soils having pH <6.0.

Cuhel et al. (2010) found that the $N_2O/ (N_2O+N_2)$ ratio increased with decreasing pH due to changes in the total denitrification activity and significant relationships were observed between *nirS*, *napA*, and *narG* gene copy numbers and the $N_2O/ (N_2O+N_2)$ ratio. According to Van Den Heuvel et al. (2011) the soil pH could be used as a predictive tool for average $N_2O$ emissions in the riparian ecosystem and the occurrence of low pH spots may explain $N_2O$ emission hotspots. Their results showed a negative exponential relationship for soil pH against $N_2O$ emissions under field condition. According to them in incubations, $NO_3^-$ reduction and $N_2$ production rates increased with pH and net $N_2O$ production rate was highest at pH 5. $N_2O$ reduction to $N_2$ was halted until $NO_3^-$ was depleted at low pH values, resulting in a built up of $N_2O$.

### 2.2.5. Soil mineral N

$NH_4^+$ and $NO_3^-$ are the key substrates for nitrification and denitrification (Granli and Bockman, 1994). Speir et al. (1995) investigated the formation of $N_2O$ and $N_2$ in soil cores treated with (13)N-labeled $NO_3(-)$ and $NH_4(+)$ maintained under aerobic conditions using a gas-stripping procedure with air as the stripping and carrier gas. Gas emission rates were always greater from $NO_3(-)$ than from $NH_4(+)$. With both substrates, $N_2O$-to-$N_2$ ratios were initially very high and then generally declined. Kusa et al. (2002) studied the nitrous oxide emissions for 6 years from a gray lowland

soil cultivated with onions in Hokkaido, Japan and concluded that the main process behind the large $N_2O$ emission near harvesting is probably denitrification rather than nitrification; this is suggested by the high ratio of $N_2O$ to NO and the dominance of soil $NO_3^-$. Following synthetic urine applications, Muller and Sherlock (2004), observed that with ammonium ($NH_4^+$) and nitrate ($NO_3^-$) applications to a German grassland ecosystem, approximately 31, 16, and 5%, respectively, of the total emitted $N_2O$ was produced by nitrification with the rest being produced by denitrification. Ambus (2005) while investigating the relationship between gross nitrogen cycling and nitrous oxide emission in grass-clover pasture observed that evolution of $15N_2O$ was positively correlated with soil $15NH_4^+$ availability and inversely related to soil $15NO_3^-$ availability and at least 50%-100% of the $N_2O$ was derived from the soil $NH_4^+$ pool.

Dong and Nedwell (2006) studied the rates of denitrification and nitrous oxide formation, and the sources of $N_2$ and $N_2O$, by the isotope-pairing technique in three U.K. estuaries. Generally, both denitrification and $N_2O$ formation decreased down the estuary as nitrate concentrations lowered. Ambus et al. (2006) reported nitrate ($NO_3^-$) to be the dominant substrate for $N_2O$ production with an average contribution of 62% and the average contribution of ammonium ($NH^+_4$) to $N_2O$ production averaged 34% from European forest soils. Rates of nitrate uptake and denitrification were measured in nine tropical low-order streams with contrasting land use in Puerto Rico by Potter et al. (2010). They observed that denitrification accounted for 1–97% of nitrate uptake showing that denitrification is a substantial sink for nitrate in tropical streams

### 2.2.6. Fertilizer application

The global synthetic N fertilizer consumption is reported to increased from ~10 Tg N since 1950s to ~100 Tg N in 2008 (Robertson and Vitousek, 2009), with the global N input into agricultural systems from synthetic fertilizer increasing more than 40 fold since 1930 (Mosier et al., 1999). Agricultural $N_2O$ emissions are considered to arise from soils amended with nitrogen-rich amendments which release inorganic nitrogen (N) in the soil (Breitenbeck and Bremner, 1986; Yan et al., 2001; Lampe et al., 2006).

Several field studies in row-crop agriculture have showed that increasing the rate of N fertilizers application results higher $N_2O$ emissions (MacKenzie et al., 1998; Bouwman et al., 2002; McSwiney and Robertson, 2005; Drury et al., 2008; Millar et al., 2010). Increased $N_2O$ emissions were recorded from a paddy rice–winter wheat rotation agroecosystem following synthetic N fertilizer and crop residue application in southeast China (Zou et al., 2005b). $N_2O$ emissions from a maize-wheat rotation field were monitored by Ding et al. (2007) and observed that the application of fertilizer N significantly increased the $N_2O$ emission, from 636 g $N_2O$-N $ha^{-1}$ $year^{-1}$ in the unfertilized soil to 4480 g $N_2O$-N $ha^{-1}$ $year^{-1}$ in the soil treated with 250 kg N $ha^{-1}$. However, this increase primarily occurred during the maize growing season. They suggested that reducing the application rate of basal fertilizer N during the maize growing season could decrease $N_2O$ emission. The highest amount of nitrogen and phosphorous fertiliser doses were considered to detect $N_2O$ emission from the interaction of N and P fertilisers under an irrigated rice system (Iqbal, 2009). His results conclude that an optimum rate of 180 kg N $ha^{-1}$ and 40 kg P $ha^{-1}$ is effective in reducing N losses through $N_2O$ emission and maintain crop yields compared to the traditionally high N rates (240 and 360 kg N $ha^{-1}$).

Reduced $N_2O$ emissions with split N application compared with a single N application in a grassland soil is observed (McTaggart et al., 1997). Hao et al. (2001) reported that spring N application have lower $N_2O$ emissions compared to fall N application in wheat (*Triticum aestivum* L.) and canola (*Brassica napus* L.). However, Yan et al. (2001) observed no significant effect of split N application on $N_2O$ emissions from maize under low rainfall conditions, but suggested that a significant benefit from split N application would be expected under normal rainfall patterns. Burton et al. (2008) reported that the timing of fertilizer nitrogen (N) application influences the availability of $NO_3^-$ as a substrate for denitrification and $N_2O$ emission. They examined the effect of split application of fertilizer N on $N_2O$ emissions and denitrification rate in potato production over 2 year and concluded that the split N application is an effective strategy for reducing $N_2O$ emissions in years where there was significant rainfall during the period between planting and hilling.

The fertilizer nitrogen form also plays an important role in regulating $N_2O$ emission (Clayton et al., 1997; Henauit et al., 1998; Bouwman et al., 2002; Tenuta and

Beauchamp, 2003; Venterea et al., 2005; Snyder et al., 2007). Field studies have showed that the $N_2O$ emissions induced by application of fertilizer N as anhydrous ammonia was 13 times higher than that induced by aqueous ammonia or urea. Whereas, the $N_2O$ emission induced by anhydrous ammonia was more than 17 times that induced by the same amount of N as calcium nitrate (Breitenbeck and Bremner, 1986). Yan et al. (2001) observed that $N_2O$ fluxes from incorporation of urea into the plough layer at 250 kg N $ha^{-1}$ by two applications and band application of urea at a depth of 8 cm at 75 kg N $ha^{-1}$ plus incorporation of urea into the plough layer at 75 kg N $ha^{-1}$, peaked following the incorporation of supplementary fertilizer, and declined to the background level after that, while the $N_2O$ flux from, band application of polyolefin-coated urea at a depth of 5 cm at 150 kg N $ha^{-1}$ was relatively low but remained at a constant level until shortly after harvest. $N_2O$ emissions were reported to be higher from injected fertilizers as compared to surface broadcast fertilizers and emissions were lower for nitrate-based fertilizers than for anhydrous ammonia (Bouwman et al., 2002). Venterea et al. (2005) showed significantly higher $N_2O$ emissions in spring applied anhydrous ammonia treatments as compared to urea–ammonium–nitrate (UAN) and broadcast urea treatments.

Josileia et al. (2010) investigated the effects of different mineral N sources like urea, ammonium sulphate, calcium nitrate, ammonium nitrate, uran, controlled-release N fertilizer, and urea with urease inhibitor on $N_2O$ fluxes from Gleysol in the South of Brazil. They observed greatest emissions for N-nitric based fertilizers, while N sources with a urease inhibitor and controlled release N presented the smallest values and the N-ammonium and amidic were intermediate. Soon et al. (2011) studied the effectiveness of polymer-coated urea vs. conventional urea (urea) in minimizing nitrate accumulation in soil and nitrous oxide ($N_2O$) emission. Their results concluded that although polymer-coated urea can increase available N during the growth period and reduce $N_2O$ loss in some years compared with urea, the time of N application had a consistently greater effect than the type of urea in enhancing crop N recovery and reducing N loss to the environment.

Wei et al. (2010) suggested that the contribution of single N fertilizer alone was larger than that combination of NP (nitrogen + phosphorus) and NPM (nitrogen + phosphorus + manure). Their results further showed that the manure treatment had

relatively large biomass and grain yield and relatively low $N_2O$ fluxes and annual emissions. They concluded that from the point of agricultural production and $N_2O$ emission, manure is recommended while single N fertilization alone is not recommended for highland winter wheat, when fertilizers are applied at the time of planting. Deyan and Changchun (2010) indicated that a small amount of N fertilizer induced much more $N_2O$ evolution from freshwater wetland soil, while P fertilizer inputs appeared to stimulate the emission of $N_2O$ only during the first few days of the experiment. Additionally, soil that was treated with P appeared to absorb $N_2O$ when it was at 60% WHC after around 6 weeks of the incubation, which indicates that the input of P fertilizer might serve as a shift of source or $N_2O$ sink in wetland soils under non-flooded conditions.

Recently, Rafique et al. (2011), while estimating $N_2O$ emission from grassland soils observed large temporal variations within each site and between sites, depending on the weather conditions, soil type and management practices. At an N applied of approximately 300 kg $ha^{-1}$ $y^{-1}$, the $N_2O$ emissions are approximately 5.0 kg $N_2O$-N $ha^{-1}$ $y^{-1}$. Whereas, the $N_2O$ emissions double to approximately 10 kg N $ha^{-1}$ for an N applied of 400 kg N ha-1 y-1. They suggested that N application below 300 kg $ha^{-1}$ $y^{-1}$ and restricted grazing on seasonally wet soils will reduce $N_2O$ emissions. Similar results of increased $N_2O$ emissions were reported from fertilized grazed grasslands soils in other studies (Velthof et al., 1996; Dittert et al., 2005; Lampe et al., 2006; Zhang and Han, 2008; Cardenas et al., 2010).

### 2.2.7. The influence of plants on $N_2O$ emission

Studies have shown that plants can significantly influence both the processes of nitrification and denitrification by affecting availability of soil $NO_3^-$, labile C compounds, $O_2$, population of nitrifiers and denitrifiers (Gregory and Atwell, 1991; Del Grosso et al., 2000; Kuzyakov and Domanski, 2000; Kirk and Kronzucker, 2005) as well as $CO_2$ resulting from rhizorespiration (Kuzyakov and Domanski, 2002; Kuzyakov, 2006). This influence will differ with the plant type as rhizodeposition and rhizorespiration vary between species (Conrad et al., 1983). The intensity and species

composition of cropping systems may also affect soil $N_2O$ emissions due to the impact of plants on soil N and C cycling and soil water content (Pathak, 1999). The role of growing plants in $N_2O$ production and emissions from agricultural systems have been documented (Muller, 2003; Baruah et al., 2010a). Mosier et al. (1990) has indicated that the young rice plants facilitate the efflux of $N_2$ and $N_2O$ from flooded paddy soil to the atmosphere. Zou et al. (2005c) observed a linear relationship between $N_2O$ emission coefficient factor and plant dark respiration rate and suggested that in the absence of photosynthesis, some $N_2O$ production in plant N assimilation was associated with plant respiration. This has indicated an important role for higher plant in $N_2O$ exchange.

In an investigation Ishikawa et al. (2003) observed that the population of ammonium oxidizing bacteria (ABO) and $N_2O$ emission from the soil were significantly lowered where *Brachiaria humidicola* has been grown compared to *B. decumbens* and *Melinis minutiflora.* They suggest that root exudates and soil extracts of *B. humidicola* suppressed AOB populations. The results obtained by Gill et al. (2006) have showed inhibitory effect of wheat varieties and stimulatory effect of chickpea varieties on potential nitrification and nitrate reductase activity (NRA) of the rhizospheric soil. On an average, NRA of the rhizospheric soil of wheat varieties decreased by 50% compared to unplanted soil. In contrast to wheat, chickpea varieties caused 5-30 times increase in NRA as compared to unplanted soil. Wang et al. (2008) observed that root structure of plant species *Zizania latifolia* effects ammonia-oxidizing bacteria in wetland soils and stimulate $N_2O$ emission.

Experiments have showed that plants can transport dissolved gases from the root zone to the atmosphere (Chang et al., 1998, Yan et al., 2000). The results obtained by Yu et al. (1997) have indicated that $N_2O$ produced in soil can be conducted to the atmosphere via rice plants similarly as $CH_4$ transport. They observed that more than 80% of both $N_2O$ and $CH_4$ were emitted through rice plants. The rest was emitted through the soil/water/atmosphere interface by ebullition and diffusion. Rusch and Rennenberg (1998) observed $N_2O$ emission through the bark of the wetland tree species black alder (*Alnus glutinosa*), when the gas concentration in the soil solution was above the ambient concentration. They suggested that the gases diffuse through the aerenchyma of the bark. According to Yan et al. (2000) the main pathway

of $N_2O$ emission from rice soil system depends on the soil water status. Under flooded condition emission takes place predominantly through the rice plants, while in the absence of flood water, emission mainly occurs through the soil surface. Ferch and Romheld (2001) investigated transport of $N_2O$ via transpiration flow in sunflower and concluded that plants can transport $N_2O$ with the transpiration stream from roots to shoots with a subsequent release through opened stomata during day time. Miao et al. (2004) studied the $N_2O$ emission rates, photosynthesis, respiration and stomatal conductance of the dominant tree species from Korean pine forest. Their results showed that the stomatal conductance, net photosynthetic rate and $N_2O$ emission of leaves were significantly reduced under the water stress. The stoma in the leaves of trees is the main pathway of $N_2O$ emission. $N_2O$ emission in the trees mainly occurred during daytime.

Li et al. (2011) measured plant and soil $N_2O$ fluxes to quantify the roles of plants and soil in the $N_2O$ budget of a cropland in North China. They observed that the plant flux was about 10% and 26% to the total ecosystem flux, for the cotton and the soybean field and suggested that ignoring the contribution of plants would cause an obvious underestimation on the ecosystem $N_2O$ flux. Their results showed that in the cotton field, the responses of plant $N_2O$ flux to some environmental factors were different under sunlight and darkness, suggesting that stomatal activity might influence the release process. Further study showed that plant $N_2O$ flux had no relationships with soil nitrate content. It was implied that $N_2O$ might not be produced by nitrate reduction in plants but primarily produced in the soil and released to the atmosphere via shoots.

# Chapter 3
# MATERIALS AND METHODS

# 3. MATERIALS AND METHODS

In the present investigation, experiments were conducted in North Bank Plain Agroclimatic Zone (NBPAZ) of Assam at Tezpur, India. The details of materials and methods employed during investigation are described below.

## 3.1. Experiment No. 1: Nitrous oxide emission estimation from autumn rice (*Ahu*) ecosystem and plant and soil parameters associated with the emission

This experiment was conducted during autumn rice growing season (May-July, 2006). The detail technical programme of this experiment is given below.

### 3.1.1. Geographical location, climatic condition and soil characteristics of the experimental site

The study was conducted in North Bank Plain Agroclimatic Zone (NBPAZ) of Assam at Tezpur, India. The experimental area is approximately situated at 26°41′ N latitude and 92°50′ E longitude in a farmer's field at about 6 km from the Tezpur University campus towards west. Figure 3.1 shows the geographical location of the experimental site located at the NBPAZ, northeast India. This zone occupies an area of 14424 $km^2$ and falls in the sub-tropical climatic region, and enjoys monsoon type of climate. Summers are hot and humid. Winters extend from the month of October to February, and are cold and generally dry. The average weekly rainfall and maximum, minimum average air temperature recorded during the experimental periods are presented in Figures 3.2. The zone is characterized by light textured loamy alluvial soils. The soil physiochemical properties of the experimental site are presented in Table 3.1.

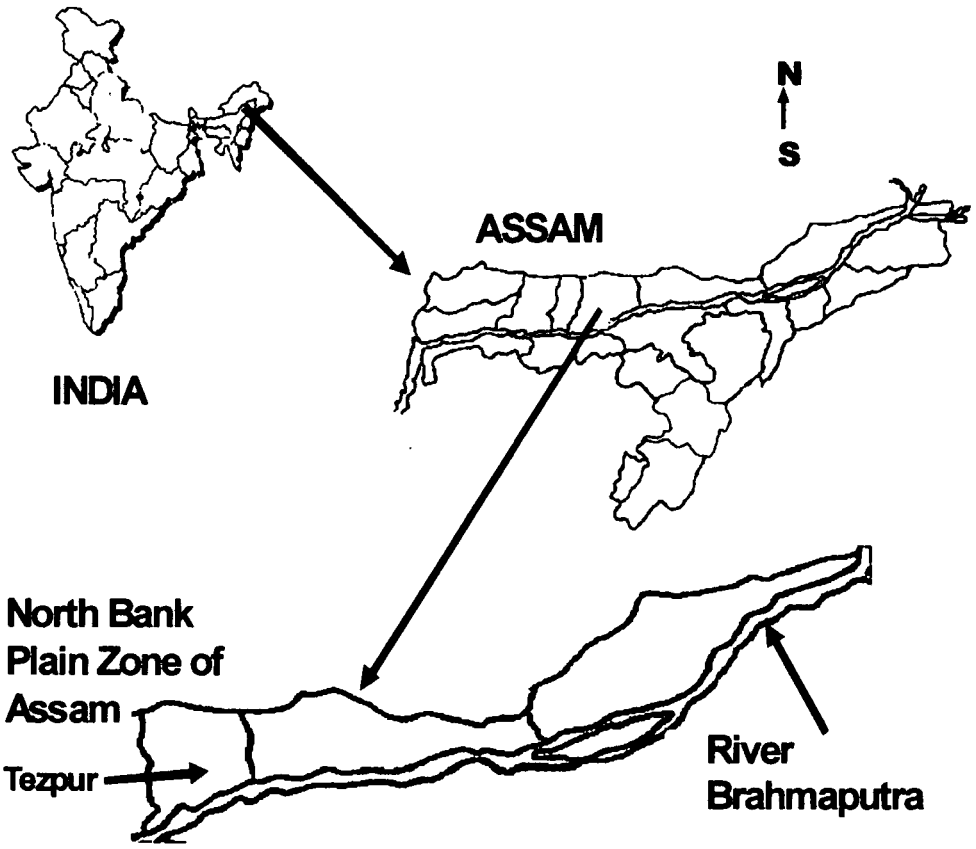


**Fig. 3.1. Experimental site at North Bank Plain Agroclimatic Zone (NBPAZ) of Assam, northeast India.**

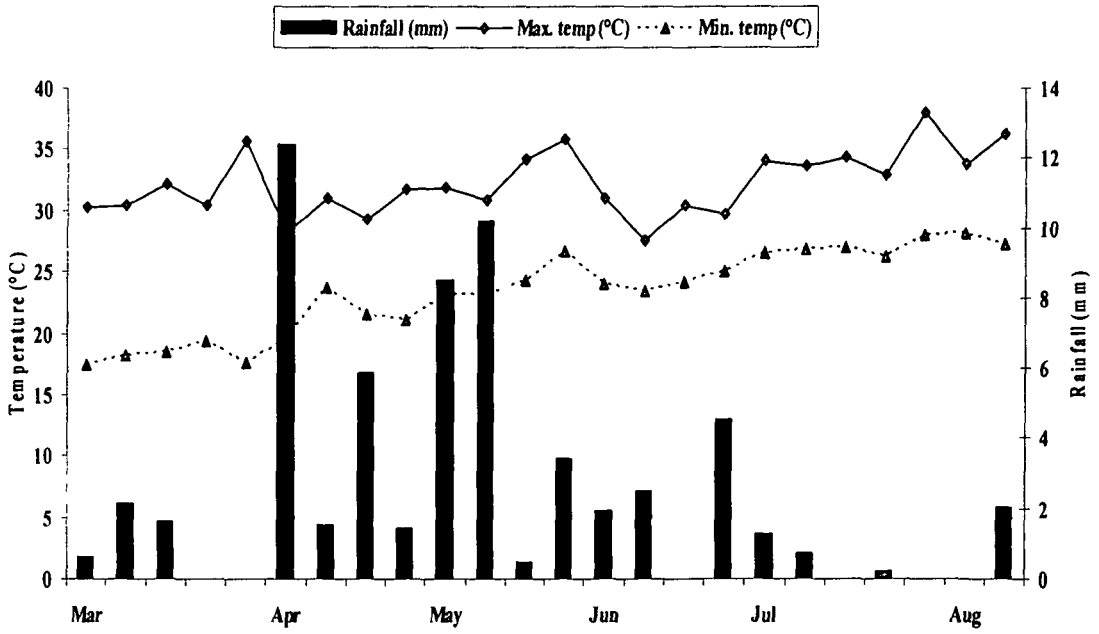


**Fig. 3.2. Meteorological parameters during the experimental period of autumn rice ecosystem.**

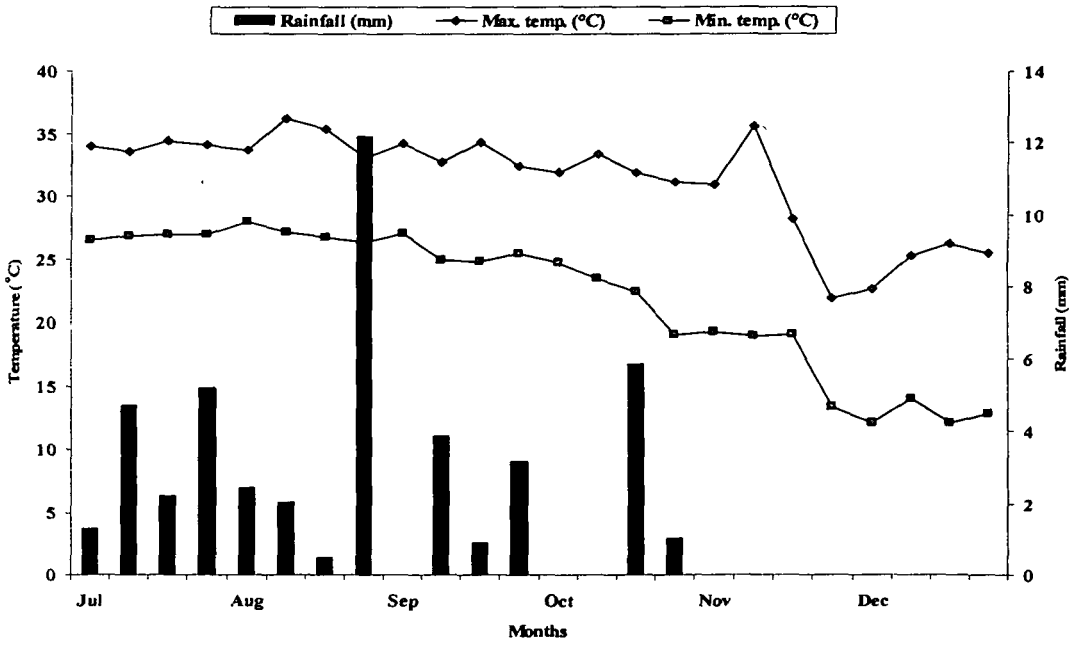


**Fig. 3.3. Meteorological parameters during the experimental period of monsoon rice ecosystem.**

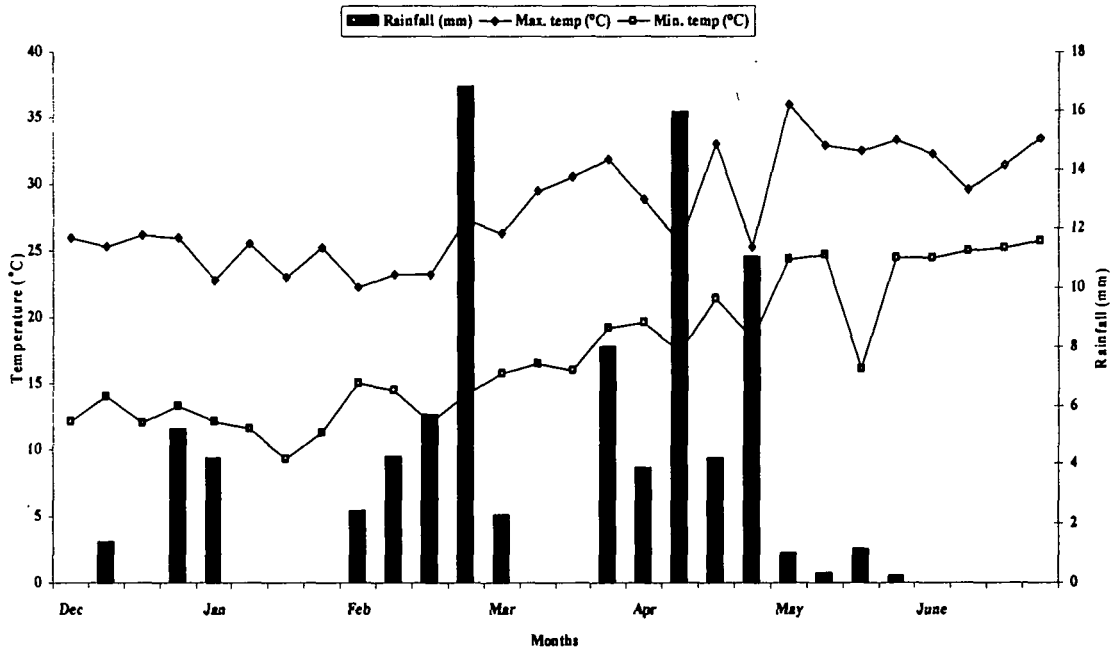


**Fig. 3.4. Meteorological parameters during the experimental period of rain-fed wheat and summer rice ecosystem.**

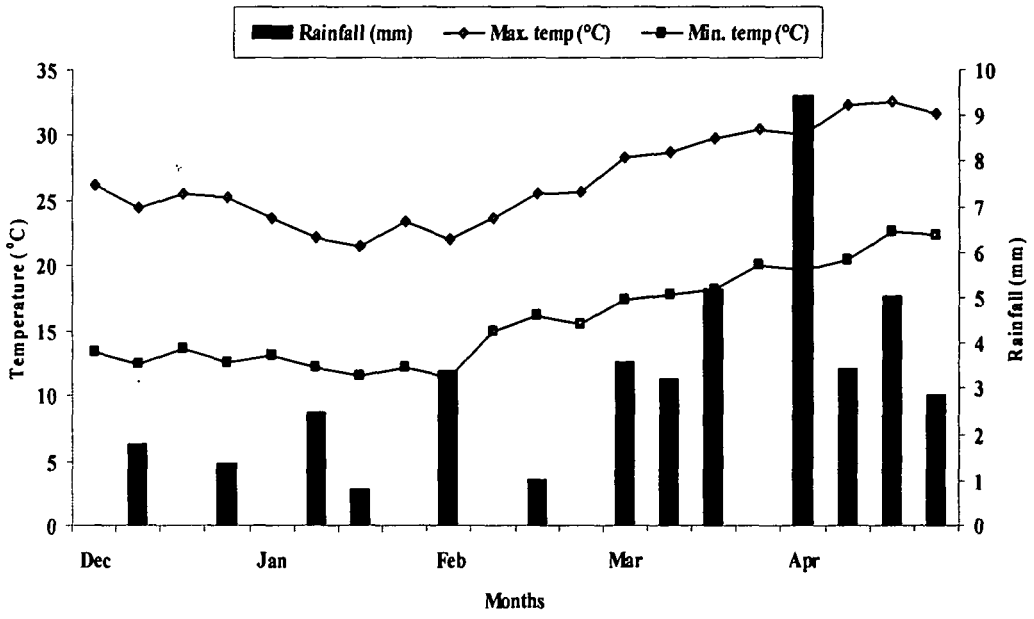


**Fig. 3.5. Meteorological parameters during the experimental period of irrigated wheat ecosystem.**

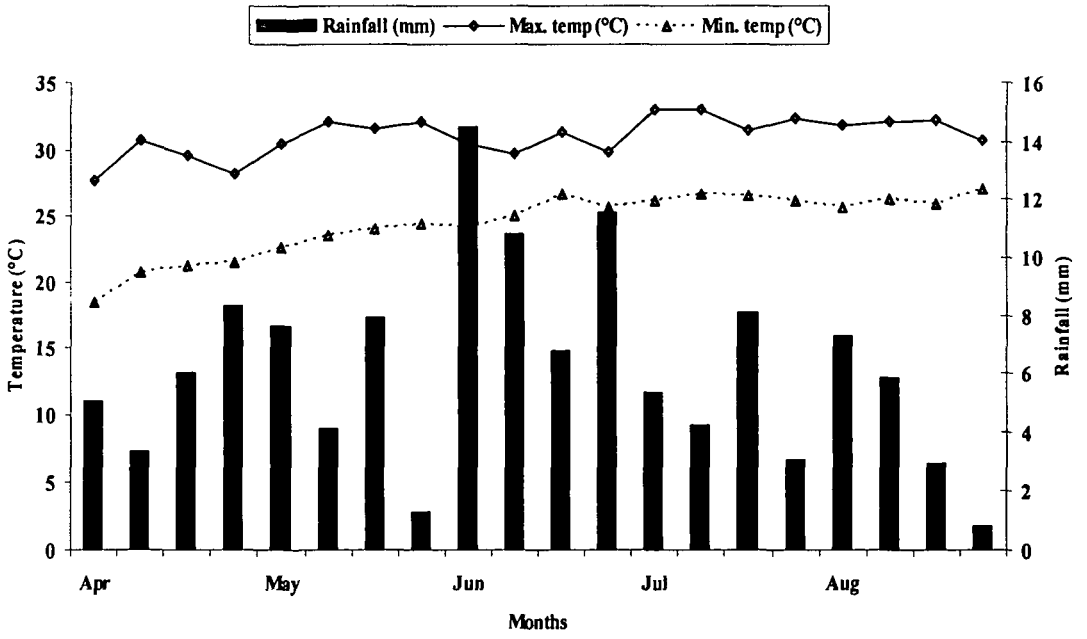


**Fig. 3.6. Meteorological parameters during the experimental period of autumn rice ecosystem with different form and doses of fertilizer treatments.**

### 3.1.2. Selection and description of rice varieties

Five popularly grown rice varieties namely Luit ($V_1$), Disang ($V_2$), Kapilli($V_3$), Siana ($V_4$) and Phorma ($V_5$) were selected for the experiment. The description of these rice varieties are given below.

1. Luit ($V_1$): This variety was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, Jorhat, India, by cross combination between 'Heera' and 'Annada'. This variety is recommended for flood-prone areas in *Ahu* season (April-July). It is a semi-dwarf, white kernelled photoperiod insensitive variety. Duration an average yield under ideal field condition is 95-100 days and 35-40 q $ha^{-1}$ respectively.

2. Disang ($V_2$): This variety was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, Jorhat, India, by cross combination between 'Lachit' and 'Kalinga III'. This semi-dwarf variety is recommended for flood-prone areas before the onset of flood in *Ahu* season. Duration and average yield under ideal field condition is 95-100 days and 35-40 q $ha^{-1}$ respectively.

3. Kapilli ($V_3$): It was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, Jorhat, India, by cross combination between 'Heera' and 'Annada'. This variety is recommended for chronically flood affected areas in *Ahu* season. It is a semi-dwarf and photoperiod insensitive variety. The kernels are white and duration and average yield under ideal field condition is 95-100 days and 35-40 q $ha^{-1}$ respectively.

4. Siana ($V_4$): It is an indigenous traditional rice cultivar generally grown under rainfed condition. Plants are of medium height. It is photoperiod insensitive. Grains are straw colored, awnless, coarse and red kernelled.

5. Phorma ($V_5$): It is an indigenous traditional rice cultivar generally grown under rainfed condition. Plants are of medium height with strong culm and good tillering ability. Photoperiod insensitive. Grains are straw colored, awnless, medium and red kernelled.

### 3.1.3. Field preparation and experimental design

Seeds of five popularly grown rice varieties namely Luit, Disang, Kapilli, (high yielding varieties); Siana and Phorma (local varieties) were sown in the nursery bed on April 3, 2006. The main field, after the previous harvested rice crop was thoroughly ploughed, laddered, puddled and two seedlings per hill of each variety were transplanted on May 4, 2006 on plots of size with 6 m × 5 m, and replicated 3 times in a randomized block design at a spacing of 20 cm ×15 cm (row to row and plant to plant). Fertilizers were applied as per package of practice of the Department of Agriculture, Government of Assam, India at the rate of 40:20:20 Kg N-$P_2O_5$-$K_2O$ per ha in the form of urea, single super phosphate and muriate of potash. One third of total dose of urea was applied at the time of final puddling before transplanting along with full dose of single super phosphate ($P_2O_5$) and muriate of potash ($K_2O$). The second and third doses of urea were applied at tillering and panicle initiation stage i.e. at 30 and 47 days after transplanting (DAT) of the crop. The crop was harvested on July 22, 2006.

### 3.1.4. Gas sampling and estimation of Nitrous oxide emission

Gas samples were collected by a closed chamber technique as described by Buendia et al. (1997). Perspex chambers (50 cm length, 30 cm width and 70 cm height for semi dwarf varieties and 50 cm length, 30 cm width and 100 cm height for tall varieties) made of 6 mm thick acrylic sheets were used for gas sampling. The rectangular U shaped aluminium channel (50 cm × 30 cm) supported on an aluminium frame (50 cm × 30 cm × 15 cm) was used to accommodate the chamber. Three chambers per plot were used. The aluminium channel was inserted into the soil to a depth of 15 cm well in advance (7 day before transplanting). Six hills of rice plants (two seedlings per hill) were enclosed inside 1 channel. The aluminium trays were filled with water to a depth of 2.5 cm, during gas sampling, which acted as air seal when the chambers were placed on the tray. A battery-operated fan was fixed inside each chamber to homogenize the air. The temperature inside the chamber was

recorded at the time of sample collection using a thermometer which was fixed inside the chamber for the calculation of box volume at STP. The gas samples were drawn with the help of a 50 ml airtight syringe fitted with a three-way stop cork at fixed interval of 0, 15, 30 and 45 minutes, once in morning at 0900 hours and again at 1400 hours. During each sampling period soil temperature and field water level was recorded. The samples were collected from the first date of transplanting of the crop till two weeks after harvest at a seven-day interval. The collected gas samples were brought to the laboratory and analysed for $N_2O$ fluxes, using a Varian model 3800 gas chromatograph (USA) fitted with an electron capture detector (ECD) and stainless steel chromopack capillary column (50 cm long, 0.53 mm out side and 1μm inside diameter). The operating temperature of the column, injector and detector were 80°C, 200°C, and 300°C, respectively. $N_2O$ flux was calculated using the formula:

$$F = \frac{\Delta x}{10^6} \times BV(STP) \times \frac{44 \times 10^3}{22400} \times \frac{1}{A} \times \frac{60}{t}$$

Where, $F$ is the efflux of nitrous oxide in mg $m^{-2}$ $h^{-1}$, $\Delta x$ is the change in concentration of nitrous oxide in ppbv from time '0' to '$t$' min, $A$ is the area within the chamber in $m^2$ and *BV(STP)* is the box air volume at standard temperature and pressure in $cm^3$.

$$BV(STP) = \frac{BV \times BP \times 273}{(273 + T) \times 760}$$

$BV$ (Box air volume) was calculated by:

$$BV = [(H - h)LW - \text{Biomass volume inside box}]$$

Where, $H$ is box height (cm), $h$ is water level above the channel (cm), $L$ = box length (cm), $BP$ is barometric pressure (mm Hg), $T$ is box air temperature at the time of sampling (°C).

The average of morning and evening fluxes were considered as the flux value for the day and expressed as μg $N_2O$-N $m^{-2}$ $h^{-1}$. Cumulative $N_2O$ emission for the

entire crop growth period was computed by the method given by Naser et al. (2007) by using the following formula.

$$\text{Cumulative emission} = \sum_{i=1}^{n-1} (R_i \times D_i)$$

Where, $R_i$ is the mean gas emission, $D_i$ is the number of days in the sampling interval and $n$ is the number of sampling times. Cumulative $N_2O$ emission is expressed as seasonal integrated flux ($E_{sif}$) in mg $N_2O$-N $m^{-2}$.

### 3.1.5. Morphological parameters

**3.1.5.1.** All the morphological parameters were recorded at weekly interval.

#### 3.1.5.1.1. Plant height

Ten (10) plants were randomly selected from each replication and height was measured from base of the plant to the top of the uppermost leaf. The average height is expressed as plant height (cm $plant^{-1}$).

#### 3.1.5.1.2. Tiller number per hill

Ten (10) hills were randomly selected from each replication and the numbers of tillers were counted. Hill means a hole where the seedlings are planted in the muddy soil. The average tiller numbers of hills were expressed as tiller number $hill^{-1}$.

#### 3.1.5.1.3. Leaf number per hill

Ten (10) hills were randomly selected from each replication and the numbers of leaves were counted. The average leaf numbers of hills were expressed as leaf number $hill^{-1}$.

#### 3.1.5.1.4. Leaf area per hill

Total leaf area per hill was measured with a portable laser leaf area meter (CID, Model CI-203). The average leaf area of ten hills from each replication were taken and expressed as leaf area ($cm^2$ $hill^{-1}$).

#### 3.1.5.1.5. Root length and root volume

Total root length per hill was measured by a portable laser leaf area meter (CID, Model CI-203) with root measurement attachment. The average root length of ten hills from each replication were taken and expressed as root length (cm $hill^{-1}$). Root volume was determined by standard water displacement method. The average root volume of ten hills from each replication were taken and expressed as root volume (ml $hill^{-1}$).

#### 3.1.5.1.6. Shoot and root dry weight

Ten (10) hills from each replication were uprooted and root portion was carefully separated from shoot portion and washed thoroughly to remove sand and soil particles under running water over a sieve. The samples were dried in an oven at 75 ± 2°C till a constant weight. The average shoot and root dry weight of ten hills from each replication were expressed as dry weight (g $hill^{-1}$).

### 3.1.6. Yield and yield attributing parameters

#### 3.1.6.1. Panicles per square meter

Numbers of panicles were recorded from randomly selected area of $1m^2$ in each replication and average value is expressed as panicle square $meter^{-1}$.

#### 3.1.6.2. Panicle length

Panicle length was measured from the nodal base of the panicle to the tip of the main rachis excluding the awn. Average length of panicles from ten plants of each replication was taken and expressed as panicle length (cm).

#### 3.1.6.3. Number of unfilled grains per panicle

The number of unfilled grains was worked out by subtracting the number of well filled grains out of total grains, from ten randomly selected panicles from each replication. The total numbers of grains per panicle were obtained by counting both filled and unfilled grains together from ten randomly selected panicles from each replication. The average value was recorded and percent sterility value was calculated by using the formula as:

$$\text{Sterility (\%)} = \frac{\text{Unfilled grains per panicle}}{\text{Filled} + \text{Unfilled grains per panicle}} \times 100$$

#### 3.1.6.4. Thousand grain weight

At harvest, the average thousand grain weight of ten samples from each replication were determined and expressed as thousand grain weight (g).

### 3.1.6.5. Yield

The mature plants were harvested from one square meter area from central part of each replicated plot. Grains were separated from straw and weighted. The average grain yield is expressed in q $ha^{-1}$.

### 3.1.7. Soil physico-chemical properties

Prior to inception of the experiment, soil samples were collected randomly from different sites from a depth of 15 cm, for analysis of cation exchange capacity, determination of soil texture, bulk density and soil nutrient content. For weekly soil analysis during crop growth samples were collected from the root zone of plants from each replication using a core sampler. Samples collected from different plots are mixed thoroughly and made one composite sample. Composite soil samples were air dried under shade, ground and passed through a 2 mm sieve. The sieved soil samples were subsequently used for analysis.

### 3.1.7.1. Soil pH

Soil pH was measured at 1:2.5 soils to water ratio using a digital pH meter (Systronics Griph model D pH meter) during each nitrous oxide sampling period.

### 3.1.7.2. Cation exchange capacity

CEC of the soil samples prior to the inception of the experiment were determined by Distillation method (Jackson, 1973). The cation exchange capacity is measured by leaching the soil with 1N $NH_4$ OAc (pH 7.0) and thereby saturating the exchange complex with $NH_4^+$ ion and then washing out the excess salts with an electrolyte free solvent i.e. alcohol. The adsorbed $NH_4^+$ is distilled with magnesia

(MgO) and the ammonia gas evolved during the distillation is absorbed in a known excess of standard acid, the excess of which is back titrated with standard alkali.

### 3.1.7.3. Bulk density

Bulk density of soils prior to the inception of the experiment was determined by core method (Blake and Hartge, 1986).

### 3.1.7.4. Determination of sand, silt and clay content

Soil samples collected from experimental field before the start of the experiment were analyzed for sand, silt and clay content by International Pipette method described by Piper (1966).

### 3.1.7.5. Soil organic carbon

Organic carbon of the soil was estimated on each $N_2O$ flux measurement day at weekly interval by wet digestion method of Walkley and Black (1947). One gram of soil sample was treated with 10 ml of 1N $K_2Cr_2O_7$ solution and 20 ml concentrated $H_2SO_4$. The mixture is allowed to stand for 30 minutes. Thereafter, 200 ml of water, 10 ml of orthophosphoric acid, 10 ml NaF and 3-4 drops of diphenylamine indicator was added. The sample was titrated against 0.5 N ferrous ammonium sulphate. At the end point of titration the colour changes from blue to bright green.

### 3.1.7.6. Nitrate nitrogen in soil

Soil nitrate nitrogen content was determined on each $N_2O$ flux measurement day at weekly interval by Phenol disulphonic acid method as described by Ghosh et al.

(1983). Twenty gram of soil was shaken continuously with 50 ml distilled water. A pinch of $CaSO_4$ is added and again shaken thoroughly for a few minutes to help quick settling of soil, and the contents filtered through a dry filter paper. Clear aliquot (20 ml) is transferred to a 50 ml silica dish, evaporated to dryness on steam bath and cooled to room temperature. Three ml of phenol disulphonic acid reagent is allowed to react with the residue by rotating the dish. After 10 minutes, 15 ml of distilled water is added and stirred with a glass rod. On cooling, the contents are washed down into 100 ml volumetric flask. Ammonia (1:1) is added slowly with mixing till the solution is alkaline as indicated by the development of yellow color due to presence of nitrate. Then another 2 ml of ammonia is added and the volume made up (100 ml) with distilled water. A yellow color developed whose intensity was detected in the photo-electric colorimeter using 420 mμ (blue filter). A standard curve was prepared by using potassium nitrate and nitrate nitrogen content of soil sample was estimated from standard curve in kg $ha^{-1}$ by using following formula.

$$\text{ppm } NO_3\text{-N in soil} = \frac{S \times T}{A \times W}$$

$$\text{Kg } NO_3\text{-N per ha} = \frac{\text{ppm } NO_3\text{ - N in soil} \times 2 \times 2.47}{2.2}$$

Where,

S = μg of $NO_3$-N per 100ml of coloured complex in aliquot of sample test solution by reference to the standard calibration curve.

T = Total volume of the extracting solution equilibrated with the soil.

A = ml aliquot of soil extract taken for the development of coloured complex.

W = Mass of soil sample in g equilibrated with the extracting solution.

### 3.1.7.7. Soil nutrient content

The nutrients content of the experimental field was estimated before the start of the experiment. Soil nitrogen content was determined by Kjeldahl's method

(Jackson, 1973). Phosphorus and potassium content in soil were determined by Bray's 1 method and Flame photometric method, respectively (Jackson, 1973). Estimation of total Fe, Cu, Mn and Zn, were done in an atomic absorption spectrophotometer (Model AA200, Perkin Elmer, USA).

### 3.1.8. Statistical analysis

Statistical analyses of the data were performed using the SPSS 10.0 software package. Relationship between nitrous oxide fluxes with means of other plant and soil variables are determined by factor analysis. The factor loadings of the rotated matrix, the percentage variability explained by each factor and the communalities for each variable were determined. The significance of the difference of different parameters among the rice varieties were analysed by two-way ANOVA and subsequently by Duncans's multiple range tests.

## 3.2. Experiment No. 2: Nitrous oxide emission estimation from monsoon rice (*Sali*) ecosystem and plant and soil parameters associated with the emission

This experiment was conducted during monsoon rice growing season (July to November, 2006). The detail technical programme of this experiment is given below.

### 3.2.1. Geographical location, climatic condition and soil characteristics of the experimental site

Geographical location, climatic condition and soil characteristics of the experimental site are described in 3.1.1. The average weekly precipitation and maximum, minimum average air temperature recorded during experimental period are presented in Figures 3.3. The soil physico-chemical properties of the experimental site are shown in Table 3.1.

### 3.2.2. Selection and description of rice varieties

Ten popularly grown monsoon rice varieties of North Bank Plain Agroclimatic Zone are selected for this experiment. Out of these varieties Rashmisali ($V_1$), Bogajoha ($V_2$), Basmuthi ($V_3$), Lalkalamdani ($V_4$) and Choimora ($V_5$) are traditional rice varieties and Mahsuri ($V_6$), Moniram ($V_7$), Kushal ($V_8$), Gitesh ($V_9$), and Profulla ($V_{10}$) are high yielding varieties. The description of these rice varieties are given below.

1. Rashmisali ($V_1$): It is an indigenous traditional rice cultivar generally grown under rainfed condition during monsoon season. It is a tall variety with narrow, long and droopy leaves and is mostly photoperiod sensitive. Grains, awnless, coarse and white kernelled.

2. Bogajoha ($V_2$): It is an indigenous traditional rice cultivar generally grown under rainfed condition. Plants are tall with long and narrow leaves. Photoperiod sensitive. Grains, awnless, coarse and white kernelled.

3. Basmuthi ($V_3$): It is an indigenous traditional rice cultivar generally grown under rainfed condition. Plants are tall with long and narrow leaves. Photoperiod sensitive. Grains are straw colored, awnless, coarse and red kernelled.

4. Lalkalamdani ($V_4$): It is an indigenous traditional rice cultivar generally grown under shallow and medium deep water situation. Plants are tall with long and narrow leaves. Photoperiod sensitive. Grains are deep yellow, elongated and white kernelled.

5. Choimora ($V_5$): It is an indigenous traditional rice cultivar generally grown under rainfed condition. Plants are tall with long and narrow leaves. Photoperiod sensitive. Grains are straw colored, with traces of awns, medium and red kernelled.

6. Mahsuri ($V_6$): This cultivar was derived from the cross $T_{65}$ × Myang Ebos 6080/2 in Malaysia and released in 1971. It is a semi-dwarf variety. Grains are medium, slender, yellow brown in color. The kernels are white and yield potential is 36-40 q $ha^{-1}$.

7. Moniram ($V_7$): This variety was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, Jorhat, India, by cross combination between 'Pankaj' and 'Mahsuri'. It is a blast tolerant, non-lodging, semi-dwarf and photoperiod sensitive variety. The kernels are white and yield potential is 45-50 q $ha^{-1}$.

8. Kushal ($V_8$): This variety was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, Jorhat, India, by cross combination between 'Pankaj' and 'Mahsuri'. It is a semi-dwarf, non-lodging and photoperiod sensitive variety. The kernels are white and yield potential is 45-50 q $ha^{-1}$.

9. Gitesh ($V_9$): This variety was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, Jorhat, India, by cross combination between 'Akisali' and 'Kushal'. This semi-dwarf variety is recommended for shallow land flood-plane and flood prone areas. Average yield in ideal field condition is 50-55 q $ha^{-1}$.

10. Profulla ($V_{10}$): This variety was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, Jorhat, India, by cross combination between 'Akisali' and 'Kushal'. This semi-dwarf variety is recommended for shallow land flood-plane and flood prone areas. Average yield in ideal field condition is 50-55 q $ha^{-1}$.

### 3.2.3. Field preparation and experimental design

The experimental plot was thoroughly ploughed, puddled and leveled. Thirty days old seedlings of each variety were transplanted on 31$^{st}$ July, 2006 to plots of size 6 m × 5 m. Seedlings were manually transplanted at a density of 2 seedlings per hill at a spacing of 20 cm ×15 cm (row to row × plant to plant). Each variety was replicated 3 times in a randomized block design. Fertilizers were applied as per package of practice of the Department of Agriculture, Government of Assam, India at the rate of 40:20:20 kg N-$P_2O_5$-$K_2O$ per ha in the form of urea, single super phosphate and

muriate of potash. One third of total doše of urea was applied at the time of transplanting along with full dose of single super phosphate ($P_2O_5$) and muriate of potash ($K_2O$). Remaining one part of urea was applied at 30 days after transplanting (DAT) and the third part of urea (N) was applied at 52 DAT i.e. at panicle primordia initiation stage of the rice varieties. All varieties were harvested at 112 DAT, except Kushal, Gitesh and Profulla (harvested at 119 DAT).

### 3.2.4. Gas sampling and estimation of Nitrous oxide emission

Nitrous oxide flux was recorded from the day of transplanting (0 DAT) onwards at weekly interval. Flux measurement was continued till two weeks after harvest. Details of materials and methods employed are described in 3.1.4. (Page, 37).

### 3.2.5. Morphological parameters

Details of methodology employed for the determination of morphological parameters of plants are described in 3.1.5.

### 3.2.6. Yield and yield attributing parameters

Details of methodology employed for the determination of yield and yield attributing parameters are described in 3.1.6.

### 3.2.7. Soil physico-chemical properties

Details of methodology employed for the determination of soil physico-chemical properties are described in 3.1.7.

### 3.2.8. Statistical analysis

The Statistical Package for the Social Sciences (SPSS) version 10.0 was used to calculate the correlation (Pearson correlation) coefficient of plant physiological and soil parameters (mean of all different growth stages) with mean $N_2O$ emission from different rice varieties. The significance of the difference of different parameters among the rice varieties were analysed by one-way ANOVA and subsequently by Duncans's multiple range tests.

## 3.3. Experiment No. 3: Nitrous oxide emission estimation from rain-fed wheat ecosystem in relation to plant and soil parameters

This experiment was conducted in rain-fed wheat ecosystem (December, 2006-April, 2007). The detail technical programme of this experiment is given below.

### 3.3.1. Geographical location, climatic condition and soil characteristics of the experimental site

Geographical location, climatic condition and soil characteristics of the experimental site are described in 3.1.1. Meteorological data of the crop growing season were recorded and presented in Figure 3.4. The soil physico-chemical properties of the experimental site are shown in Table 3.1.

### 3.3.2. Selection and description of wheat varieties

Four wheat varieties were selected for this experiment viz., Sonalika, HUW 468, HUW 234 and DBW 14. Descriptions of these varieties are given below.

1. Sonalika: The parentage of wheat variety 'Sonalika' is II54.388/AN/3/YT54/N10B//LR. This variety was released in 1967, in Indian Agricultural Research Institute, New Delhi. It takes about 110-120 days to mature and suitable for early, medium and late sown under high fertility conditions both under assured and limited irrigation facilities in almost all the zones of India. Plants are erect in nature having waxy and stiff stem, light green long narrow droopy leaves. Grains are large, bold amber colored and semi hard. Average yield under ideal field condition is 50-55 q $ha^{-1}$.

2. HUW 468: The parentage of wheat variety 'HUW 468' is CPAN 1962 / TONI // LIRA's' / PRL's'. This variety is suitable for North Eastern Plains Zone (NEPZ) of India under timely sown, irrigated conditions. It is also suitable for general cultivation, zero tillage and surface seeding. It is a rust resistant variety. Grain yield under ideal field condition is 55 to 60 q $ha^{-1}$.

3. HUW 234: The parentage of wheat variety 'HUW 234' is HUW12/SPRW//HUW12. This variety was released during 1985, in BHU, Varanasi. An excellent variety for late sown under irrigated conditions adapted to North Eastern Plains Zone (NEPZ) of India. Suitable for general cultivation, zero tillage and surface seeding. It is a rust resistant variety. Grain yield under ideal field condition is 45 to 50 q ha–1.

4. DBW 14: The parentage of wheat variety 'DBW 14' is RAJ 3765/PBW343. This variety is released during 2003 in DWR, Karnal and adapted to North Eastern Plains Zone (NEPZ) of India. It is suitable under irrigated late sown conditions. Tolerant to brown and yellow rusts; karnal bunt and leaf blight. Grain yield under ideal field condition is 45 to 53 q ha–1.

### 3.3.3. Field preparation and experimental design

Seeds of wheat varieties namely Sonalika, HUW 468, HUW 234 and DBW 14 were sown in the well prepared field on December 27, 2006, at a row to row spacing of 20 cm. Each variety was replicated 3 times in a randomized block design in plot

size of 2 m x 2 m. Fertilizers were applied at the rate of 80:34:42 kg $N\text{-}P_2O_5\text{-}K_2O$ $ha^{-1}$ in the form of urea, single super phosphate and muriate of potash. A third of N and all the $P_2O_5$ and $K_2O$ were applied as basal dose by broadcasting before last ploughing and mixed thoroughly with the soil. The remaining two third of N was top dressed at crown root initiation stage, *i.e.* 25 days after sowing (DAS). One pre sowing irrigation was applied 3 days before sowing to enable quick and uniform germination of seeds. Wheat varieties were harvested on the April 7, 2007.

### 3.3.4. Gas sampling and estimation of Nitrous oxide emission

Nitrous oxide fluxes were recorded from 11 DAS (at seedling establishment) onwards at weekly interval. Flux measurement was continued until two weeks after harvest. During each sampling period soil moisture content was estimated by Gravimetric method described by Black (1965). Details of gas sampling procedure and analysis are described in 3.1.4.

### 3.3.5. Morphological parameters

Details of methodology employed for the determination of morphological parameters of plants are described in 3.1.5.

### 3.3.6. Yield and yield attributing parameters

Details of methodology employed for the determination of yield and yield attributing parameters are described in 3.1.6.

### 3.3.7. Soil physico-chemical properties

Details of methodology employed for the determination of soil physico-chemical properties are described in 3.1.7.

### 3.3.8. Statistical analysis

Statistical analyses of the data were performed using the SPSS 11.5 software package with differences in parameters, among the wheat varieties, analysed by one-way analysis of variance (ANOVA) and subsequently by Duncans's multiple range test. Correlations between $N_2O$ fluxes and means of other plant and soil variables were determined by factor analysis. The factor loadings, the percentage variability explained by each factor and the communalities for each variable were determined.

## 3.4. Experiment No. 4: Nitrous oxide emission estimation from summer rice (*Boro*) ecosystem in relation to plant and soil parameters

This experiment was conducted during summer rice growing season (February, 2007- June, 2007). The detail technical programme of this experiment is given below.

### 3.4.1. Geographical location, climatic condition and soil characteristics of the experimental site

Geographical location, climatic condition and soil characteristics of the experimental site are described in 3.1.1. The average weekly precipitation and maximum, minimum average air temperature recorded during experimental period are shown in Figure 3.4. The soil physico-chemical properties of the experimental site are shown in Table 3.1.

### 3.4.2. Selection and description of rice varieties

Three popularly grown rice varieties were selected for this experiment. The description of these rice varieties are given below.

1. Bishnuprasad ($V_1$): This variety was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, Jorhat, India, by cross combination between 'K 343-29-1-1' and 'Suweon 334'. This variety is recommended for irrigated *boro* rice growing situations. Duration an average yield under ideal field condition is 165 days and 40-45 q $ha^{-1}$ respectively.

2. Joymoti ($V_2$): This variety was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, Jorhat, India, by cross combination between 'Jaya' and 'Mahsuri'. This fine grained variety is recommended for *boro* season. Duration an average yield under ideal field condition is 175 days and 45-50 q $ha^{-1}$.

3. Kanaklata ($V_3$): This variety was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, Jorhat, India, by cross combination between 'Jaya' and 'Mahsuri'. This variety is recommended for traditional *boro* areas. Duration and average yield under ideal field condition is 165-175 days and 40-45 q $ha^{-1}$ respectively.

### 3.4.3. Field preparation and experimental Design

Three summer rice varieties were sown in a nursery bed on January 10, 2007, and after ploughing, puddling, and leveling of the field the seedlings of each variety were transplanted on February 8, 2007 to plots of size 6 m × 5 m. The seedlings were manually transplanted at a density of 2 seedlings per hill at a spacing of 20 cm ×15 cm (row to row × plant to plant). Each variety was replicated 3 times in a randomized block design. Fertilizers were applied at the rate of 60:30:30 kg $N\text{-}P_2O_5\text{-}K_2O$ $ha^{-1}$ in the forms of urea, single super phosphate, and muriate of potash. One third of the total urea dose was applied at the time of final puddling, before transplanting along with

the full dose of single super phosphate ($P_2O_5$) and muriate of potash ($K_2O$). The second and third doses of urea were top dressed 30 and 59 days after transplanting (DAT) of the crop. Rice was irrigated at the time of transplanting and 34 and 41 DAT of the crop corresponding to drop in water level in the field. Rice varieties were harvested on June 7, 2007.

### 3.4.4. Gas sampling and estimation of Nitrous oxide emission

Nitrous oxide flux was recorded from the day of transplanting (0 DAT) onwards at weekly interval. Flux measurement was continued till three weeks after harvest. Details of gas sampling procedure and analysis are described in 3.1.4. (Page no. 37).

### 3.4.5. Morphological parameters

Details of methodology employed for the determination of morphological parameters of plants are described in 3.1.5. (Page no. 39).

### 3.4.6. Yield and yield attributing parameters

Details of methodology employed for the determination of yield and yield attributing parameters are described in 3.1.6. (Page no. 41).

### 3.4.7. Soil physico-chemical properties

Details of methodology employed for the determination of soil physico-chemical properties are described in 3.1.7. (Page no. 42).

### 3.4.8. Statistical analysis

Statistical analyses of the data were performed using the SPSS 11.5 software package with differences in parameters, among the rice varieties, analysed by one-way analysis of variance (ANOVA) and subsequently by Duncans's multiple range test. Correlations between $N_2O$ fluxes and means of other plant and soil variables were determined by factor analysis. The factor loadings, the percentage variability explained by each factor and the communalities for each variable were determined.

## 3.5. Experiment No. 5: Nitrous oxide emission estimation from irrigated wheat ecosystem in relation to plant and soil parameters

This experiment was conducted in irrigated wheat ecosystem (December, 2007 to April, 2008). The detail technical programme of this experiment is given below.

### 3.5.1. Geographical location, climatic condition and soil characteristics of the experimental site

Geographical location, climatic condition and soil characteristics of the experimental site are described in 3.1.1. (Page no. 31). Meteorological data of the crop growing season were recorded and presented in Figure 3.5. The soil physico-chemical properties of the experimental site are shown in Table 3.1.

### 3.5.2. Selection and description of wheat varieties

Four wheat varieties were selected for this experiment viz., Sonalika, HUW 468, HUW 234 and DBW 14. Descriptions of these varieties are given in section 3.3.2. (Page no. 49).

### 3.5.3. Field preparation and experimental design

Seeds of wheat varieties were sown in a well prepared field on December 18, 2007, at a spacing of 20 cm (row to row). The varieties were replicated 3 times in a randomized block design in plot size of 2 m × 2 m. Fertilizers were applied at the rate of 80:34:42 kg N-$P_2O_5$-$K_2O$ $ha^{-1}$ in the form of urea, single super phosphate and muriate of potash. One third of N and all the $P_2O_5$ and $K_2O$ were applied as basal dose by broadcasting before last ploughing and mixed thoroughly with the soil. The remaining two third of N was top dressed at 20 days after sowing (DAS). A pre sowing irrigation was applied 3 days before sowing for quick and uniform germination of seeds. First irrigation was applied at 22 days after sowing (DAS), second irrigation was done at 44 DAS and third irrigation was done at 75 DAS. Crop was harvested on April 5, 2008.

### 3.5.4. Gas sampling and estimation of Nitrous oxide emission

Nitrous oxide fluxes were recorded from12 DAS onwards at weekly interval. Flux measurement was continued until two weeks after harvest. During each sampling period soil moisture content was estimated by Gravimetric method described by Black (1965). Details of gas sampling procedure and analysis are described in 3.1.4. (Page no. 37).

### 3.5.5. Morpho-physiological parameters

Transpirational rates (mmol $H_2O$ $m^{-2}$ $s^{-1}$) of leaf were measured at weekly interval from $12^{th}$ day of sowing till harvest by an infrared gas analyzer (LI-6400 portable photosynthesis system; LI-COR) under ambient environmental conditions. The middle portion of a fully expanded, second leaf from the top was used for

measurement during pre-flowering stage and after panicle initiation stage the flag leaf was used.

Details of methodology employed for the determination of other morpho-physiological parameters of plants are described in section 3.1.5. (Page no. 39).

### 3.5.6. Yield and yield attributing parameters

Details of methodology employed for the determination of yield and yield attributing parameters are described in 3.1.6. (Page no. 41).

### 3.5.7. Soil physico-chemical properties

Details of methodology employed for the determination of soil physico-chemical properties are described in 3.1.7. (Page no. 42).

### 3.5.8. Statistical analysis

The SPSS 11.5 software package was used to calculate the correlation (Pearson correlation) coefficient of nitrous oxide fluxes with means of plant and soil variables. The significance of the difference of different parameters among the wheat varieties were analysed by one-way analysis of variance (ANOVA) and subsequently by Duncans's multiple range tests.

## 3.6. Experiment No. 6: Nitrous oxide emission estimation from autumn rice (*Ahu*) ecosystem with different doses of fertilizer combinations

This experiment was conducted in autumn rice (*Ahu*) ecosystem with different doses of fertilizer combinations from May to August, 2008. The detail technical programme of this experiment is given below.

### 3.6.1. Geographical location, climatic condition and soil characteristics of the experimental site

Geographical location, climatic condition and soil characteristics of the experimental site are described in 3.1.1. The average weekly precipitation and maximum, minimum average air temperature recorded during experimental period are shown in Figure 3.6. The soil physico-chemical properties of the experimental site are shown in Table 3.1.

### 3.6.2. Selection and description of rice varieties

Two rice varieties were selected for this experiment viz., Phorma and Luit. Descriptions of these varieties are given in section 3.1.2. (Page no. 36).

### 3.6.3. Field preparation and experimental design

Seedlings of rice varieties namely Phorma ($V_1$) and Luit ($V_2$) were transplanted in well prepared plots (2m × 2m) comprising of nine different fertilizer treatment combinations, each replicated three times in randomized block design on 17 $^{th}$ May, 2008. Details of fertilizer treatment combinations are presented below in 3.6.3.1. According to the package of practice one third of total dose of N was applied at the time of final puddling before transplanting along with full dose of $P_2O_5$ and

$K_2O$. The second and third doses of N were applied at tillering and panicle initiation stages, i.e. at 30 and 47 days after transplanting (DAT) of the crop. Farm yard manure (FYM) was applied in treatments $T_7$, $T_8$ and $T_9$ @ 10 t $ha^{-1}$ along with other fertilizers at the time of final land preparation. Crop was harvested on 4 $^{th}$ August, 2008.

### 3.6.3.1 Details of treatment combinations:

The form and doses of fertilizer treatments are given below

$T_1$: N, $P_2O_5$, $K_2O$ @ 40: 20: 20 kg $ha^{-1}$ in the form of Urea, SSP, MOP

$T_2$: N, $P_2O_5$, $K_2O$ @ 35:18:18 kg $ha^{-1}$ in the form of Urea, SSP, MOP

$T_3$: N, $P_2O_5$, $K_2O$ @ 45:22:22 kg $ha^{-1}$ in the form of Urea, SSP, MOP

$T_4$: N, $P_2O_5$, $K_2O$ @ 40:20:20 kg $ha^{-1}$ in the form of Urea, DAP, MOP

$T_5$: N, $P_2O_5$, $K_2O$ @ 35:18:18 kg $ha^{-1}$ in the form of Urea, DAP, MOP

$T_6$: N, $P_2O_5$, $K_2O$ @ 45:22:22 kg $ha^{-1}$ in the form of Urea, DAP, MOP

$T_7$: N, $P_2O_5$, $K_2O$ @ 40:20:20 kg $ha^{-1}$ in the form of Urea, SSP, MOP + FYM

$T_8$: N, $P_2O_5$, $K_2O$ @ 35:18:18 kg $ha^{-1}$ in the form of Urea, SSP, MOP + FYM

$T_9$: N, $P_2O_5$, $K_2O$ @ 45:22:22 kg $ha^{-1}$ in the form of Urea, SSP, MOP + FYM

### 3.6.4. Gas sampling and estimation of Nitrous oxide emission

Nitrous oxide flux was recorded from the day of transplanting (0 DAT) onwards at weekly interval. Flux measurement was continued till two weeks after harvest. Details of materials and methods employed are described in 3.1.4.

### 3.6.5. Morphological parameters

Details of methodology employed for the determination of morphological parameters of plants are described in 3.1.5.

### 3.6.6. Yield and yield attributing parameters

Details of methodology employed for the determination of yield and yield attributing parameters are described in 3.1.6.

### 3.6.7. Soil physico-chemical properties

Details of methodology employed for the determination of soil physico-chemical properties are described in 3.1.7.

### 3.6.8. Statistical analysis

The Statistical Package for the Social Sciences (SPSS) version 11.5 was used to calculate the correlation (Pearson correlation) coefficient of plant physiological and soil parameters with mean $N_2O$ emission from different rice varieties. The significance of the difference of different parameters among the rice varieties were analysed by one-way ANOVA and subsequently by Duncans's multiple range tests.

**Table 3.1. Soil physiochemical properties of the experimental fields of different ecosystems.**

| Parameters | Ecosystems | | | | | |
|---|---|---|---|---|---|---|
| | Autumn rice | Monsoon rice | Rain-fed wheat | Summer rice | Irrigated wheat | Autumn rice (fertilizer trial) |
| Sand (%) | 28.20 ± 0.35 | 29.18 ± 0.48 | 27.25 ± 0.72 | 31.10 ± 0.38 | 28.29 ± 0.36 | 29.02 ± 0.10 |
| Silt (%) | 41.60 ± 0.35 | 40.58 ± 0.44 | 42.60 ± 0.75 | 39.30 ± 0.06 | 40.63 ± 0.56 | 40.69 ± 0.23 |
| Clay (%) | 30.20 ± 0.20 | 30.24 ± 0.14 | 30.15 ± 0.63 | 29.60 ± 0.64 | 31.08 ± 0.58 | 30.29 ± 0.66 |
| Bulk density (g $cc^{-1}$) | 0.86 ± 0.02 | 0.87 ± 0.01 | 0.81 ± 0.01 | 0.84 ± 0.01 | 0.80 ± 0.02 | 0.85 ± 0.01 |
| CEC (meq. $100g^{-1}$) | 10.15 ± 0.09 | 11.35 ± 0.06 | 13.10 ± 0.21 | 10.08 ± 0.62 | 12.45 ± 0.59 | 10.40 ± 0.13 |
| pH | 5.40 ± 0.12 | 5.30 ± 0.17 | 5.36 ± 0.05 | 5.20 ± 0.10 | 5.36 ± 0.07 | 5.20 ± 0.12 |
| Soil organic carbon (%) | 0.93 ± 0.02 | 0.94 ± 0.01 | 0.94 ± 0.01 | 0.91 ± 0.01 | 0.95 ± 0.01 | 0.91 ± 0.01 |
| Available nitrogen (Kg $ha^{-1}$) | 372.56 ± 0.79 | 376.50 ± 1.04 | 369.51 ± 0.37 | 375.06 ± 1.00 | 370.83 ± 0.44 | 376.83 ± 0.97 |
| Available phosphorus (Kg $ha^{-1}$) | 35.19 ± 0.51 | 34.28 ± 0.60 | 37.12 ± 0.48 | 34.24 ± 0.59 | 36.40 ± 0.31 | 34.97 ± 0.44 |
| Available potassium (Kg $ha^{-1}$) | 236.50 ± 0.51 | 230.60 ± 0.46 | 231.28 ± 0.36 | 239.14 ± 0.62 | 228.48 ± 0.29 | 239.83 ± 0.20 |
| Total Iron (ppm) | 443.00 ± 0.58 | 427.00 ± 0.29 | 430.00 ± 0.90 | 431.00 ± 0.29 | 436.15 ± 0.26 | 429.73 ± 0.64 |
| Total Zinc (ppm) | 24.03 ± 0.61 | 28.03 ± 0.55 | 25.03 ± 0.84 | 26.10 ± 0.35 | 23.20 ± 0.23 | 22.97 ± 0.44 |
| Total Manganese (ppm) | 21.00 ± 0.58 | 23.18 ± 0.22 | 20.05 ± 0.60 | 19.85 ± 0.57 | 22.05 ± 0.04 | 20.97 ± 0.32 |
| Total Copper (ppm) | 16.00 ± 0.87 | 15.06 ± 0.13 | 19.00 ± 0.70 | 18.05 ± 0.32 | 17.26 ± 0.41 | 19.63 ± 0.52 |

# Chapter 4
# RESULTS

# 4. RESULTS

The results of the present investigation are presented with figures and tables under the following headings.

## 4.1. Nitrous oxide emission estimation from autumn rice (*Ahu*) ecosystem and plant and soil parameters associated with the emission

### 4.1.1. Meteorological parameters

Meteorological parameters recorded during experimental period are presented in Figure 3.2. The average weekly rainfall recorded from 0.46 mm to 12.37 mm. The average minimum and maximum air temperature ranged from 17.43°C to 38.00°C. Maximum rainfall was recorded in the months of April and May which depleted during August.

### 4.1.2. Nitrous oxide flux (μg $N_2O$-N $m^{-2}$ $h^{-1}$)

The $N_2O$ emission from the rice varieties during the whole crop growing season varied from 1.24 μg $N_2O$-N $m^{-2}$ $h^{-1}$ to 379.40 μg $N_2O$-N $m^{-2}$ $h^{-1}$ (Fig. 4.1). Similar patterns of $N_2O$ emission was observed from all the rice varieties which was initially low up to 28 days after transplanting (DAT), thereafter rate of emission gradually increased in all the rice varieties and emission peaks were recorded at 35, 49 and 70 DAT corresponding to active vegetative, panicle initiation and maturity stages of the varieties. Significant variations were observed in seasonal integrated $N_2O$ flux ($E_{sif}$) among the varieties (Table 4.3). Higher seasonal emission was recorded from rice varieties Phorma (150.30 mg $N_2O$-N $m^{-2}$) and Siana (139.19 mg $N_2O$-N $m^{-2}$)

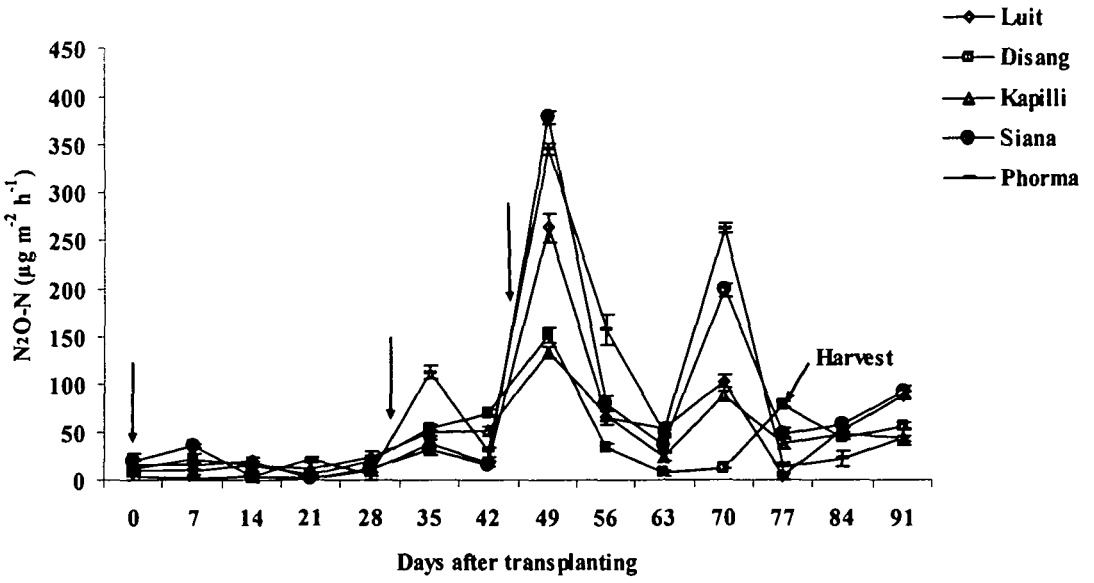


**Fig. 4.1. Nitrous oxide fluxes $N_2O$-N (µg $m^{-2}$ $h^{-1}$) from rice varieties in autumn rice ecosystem. Vertical bars represent standard error of three replications. The arrows indicate the time of application of fertilizer and day of harvest.**

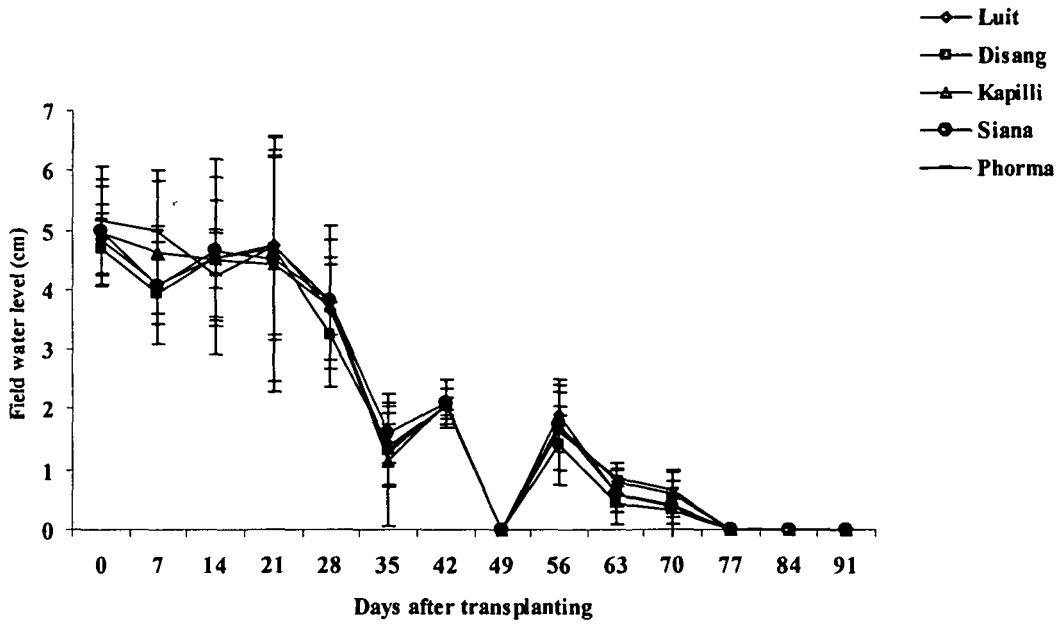


**Fig. 4.2. Standing water level of the experimental field during autumn rice growing season. Vertical bars represent standard error of three replications.**

followed by Luit (99.97 mg $N_2O$-N $m^{-2}$), Kapilli (84.68 mg $N_2O$-N $m^{-2}$) and Disang (77.14 mg $N_2O$-N $m^{-2}$).

### 4.1.3. Water level (cm)

Water level of the experimental field recorded during $N_2O$ flux measurement is presented in Figure 4.2. Field water level ranged from 0.33 to 5.18 cm during crop growing season. The water level of experimental field at initial period was considerably high due to high rainfall and slowly decreased to a minimum level at harvesting stage of crop. Significant negative correlation of water level of experimental field with $N_2O$ emission was recorded in present experiment (Table 4.1).

### 4.1.4. Soil temperature (°C)

Figure 4.3 represents the soil temperature of the experimental field. The mean soil temperature of the experimental field at the time of transplanting (0 DAT) was 26°C. Thereafter mean soil temperature gradually increased and reached a maximum value at 21 DAT (36°C). Soil temperature after panicle initiation and crop ripening stages varied between 30°C and 31°C. The relationship between soil temperature and $N_2O$ emission is however not significant (Table 4.1).

### 4.1.5. Soil organic carbon (%)

Figure 4.4 represents the soil organic carbon of the experimental field. During the crop growing season soil organic carbon content varied from 0.93% to 1.27%. The soil organic carbon of the experimental field was found to be higher between 35 to 56 DAT (active vegetative growth stage and panicle initiation stage) and thereafter it started to decrease.

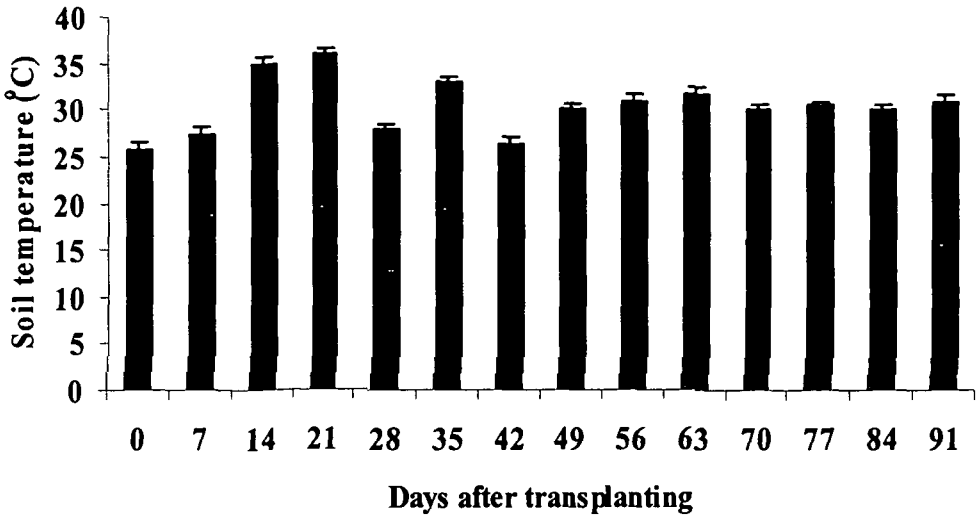


Fig. 4.3. Soil temperature (°C) of the experimental field during autumn rice growing season. Vertical bars represent standard error of three replications.

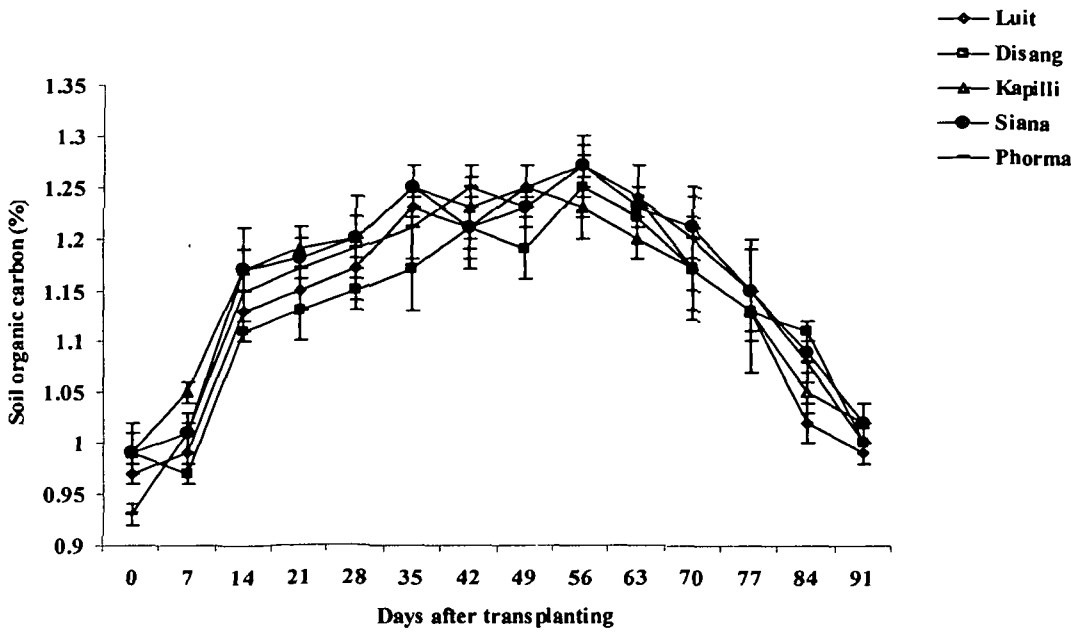


Fig. 4.4. Soil organic carbon (%) of the experimental field during autumn rice growing season. Vertical bars represent standard error of three replications.

### 4.1.6. Soil nitrate nitrogen (kg $ha^{-1}$)

Soil $NO_3^-$-N content of experiment field (Fig. 4.5) was initially low and started to increase from 35 DAT onwards and varied significantly in the plots planted with different varieties. High $NO_3^-$ content was observed in the experimental field at crop maturity stage i.e., from 70 DAT onwards.

### 4.1.7. Soil pH

The recorded soil pH of the experimental field shown in Figure 4.6 during crop growing season ranged from 5.0 to 6.4. The relationship between soil pH and $N_2O$ emission are not significant in present study (Table 4.1).

### 4.1.8. Plant height (cm)

Table 4.2 represents the plant height of rice varieties which was recorded at weekly interval from 7 DAT till harvest. Plant height gradually increased in all the rice varieties from 7 DAT onwards. High rate of increase in plant heights were recorded at the active vegetative (35 DAT) and panicle initiation (49) stages of the varieties however, after panicle initiation rate of increase in plant height gradually declined.

### 4.1.9. Tiller number ($hill^{-1}$)

Table 4.2 represents the tiller count of rice varieties. Number of tillers per hill increased up to 56 DAT with the advancement in growth and development of the varieties and declined at crop ripening stage. Variation in tiller number per hill was

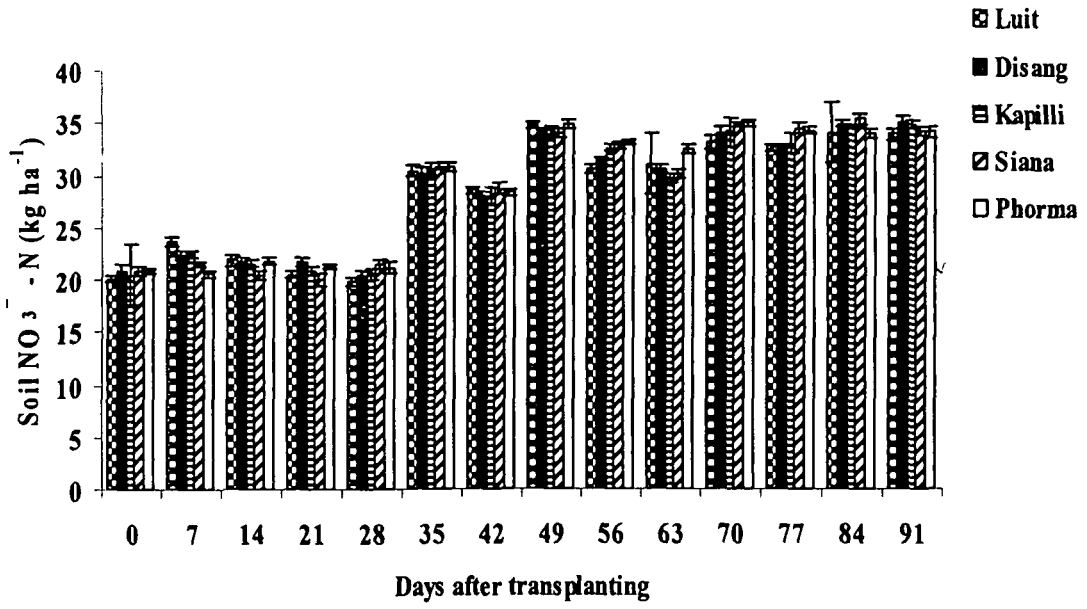


**Fig. 4.5. Soil $NO_3^-$ - N (kg ha $^{-1}$) of the experimental field during autumn rice growing season. Vertical bars represent standard error of three replications.**

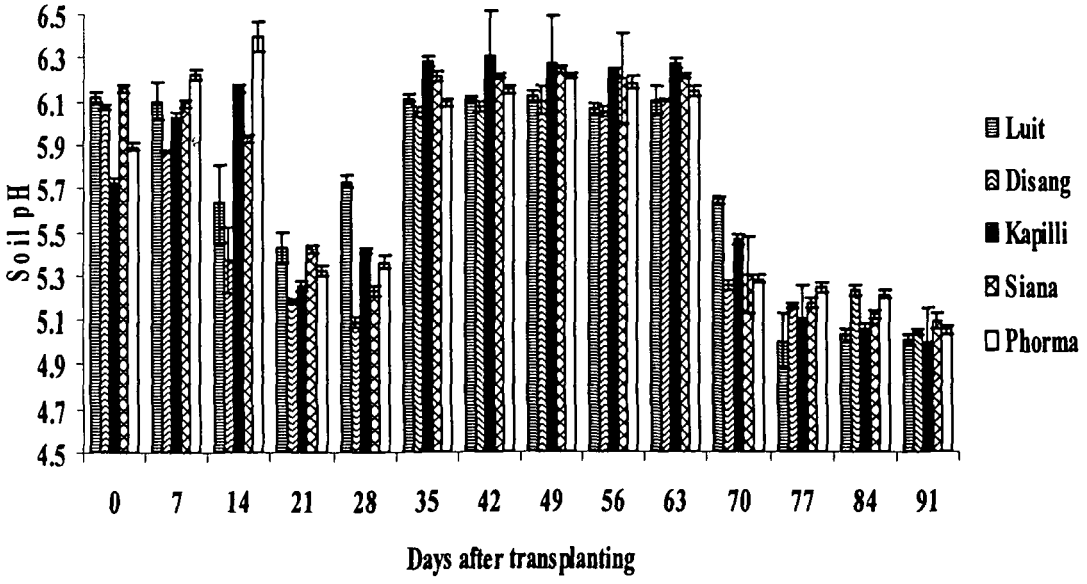


**Fig. 4.6. Soil pH of the experimental field during autumn rice growing season. Vertical bars represent standard error of three replications.**

recorded within these varieties. Among the varieties higher tiller number hill$^{-1}$ was recorded in Phorma.

### 4.1.10. Leaf number (hill$^{-1}$)

Table 4.2 represents the leaf number per hill of rice varieties. Leaf number rapidly increased in all the varieties from 7 DAT to 35 DAT. Thereafter rate of increase slowed down and leaf number started to decline after panicle initiation. There was variation in leaf number within the varieties. Among rice varieties Phorma and Siana showed higher leaf count per hill from 42 DAT up to crop harvest.

### 4.1.11. Leaf area (cm$^2$ hill$^{-1}$)

Leaf area gradually increased in rice varieties from 7 DAT onwards and reached maximum, 929.52 cm$^2$ hill$^{-1}$ and 892.95 cm$^2$ hill$^{-1}$ at 56 DAT in Phorma and Siana, respectively (Fig. 4.7). Leaf area started to decline during crop ripening stage in all varieties. At harvest (77 DAT) minimum leaf area of 343.10 cm$^2$ hill$^{-1}$ was recorded in Luit. Leaf area varied significantly within the varieties. $N_2O$ emission and leaf area recorded significant correlation in the present study (Table 4.1).

### 4.1.12. Root length (cm hill$^{-1}$)

Figure 4.8 represents the root length (cm hill$^{-1}$) of rice varieties. Root length at initial stage (7 DAT) varied between 128.31 cm to 241.60 cm in the varieties. It increased gradually from 7 DAT onwards and obtained a maximum value of 1284.56 cm, 1264.98 cm, 1188.02 cm, 1112.39 cm and 1066.79 cm in varieties Phorma, Siana, Kapilli, Disang and Luit at 63 DAT, respectively. Root length gradually decreased from 70 DAT and 77 DAT. The relationship between root length and $N_2O$ emission are significant in present study (Table 4.1).

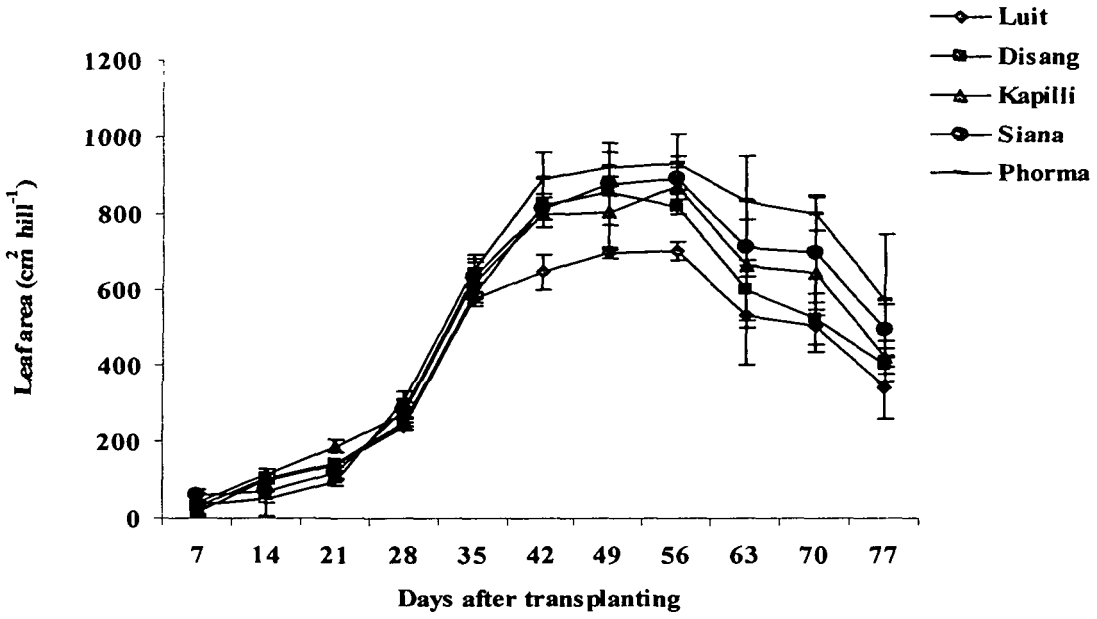


**Fig. 4.7. Leaf area (cm$^2$ hill$^{-1}$) of the rice varieties during autumn rice growing season. Vertical bars represent standard error of three replications.**

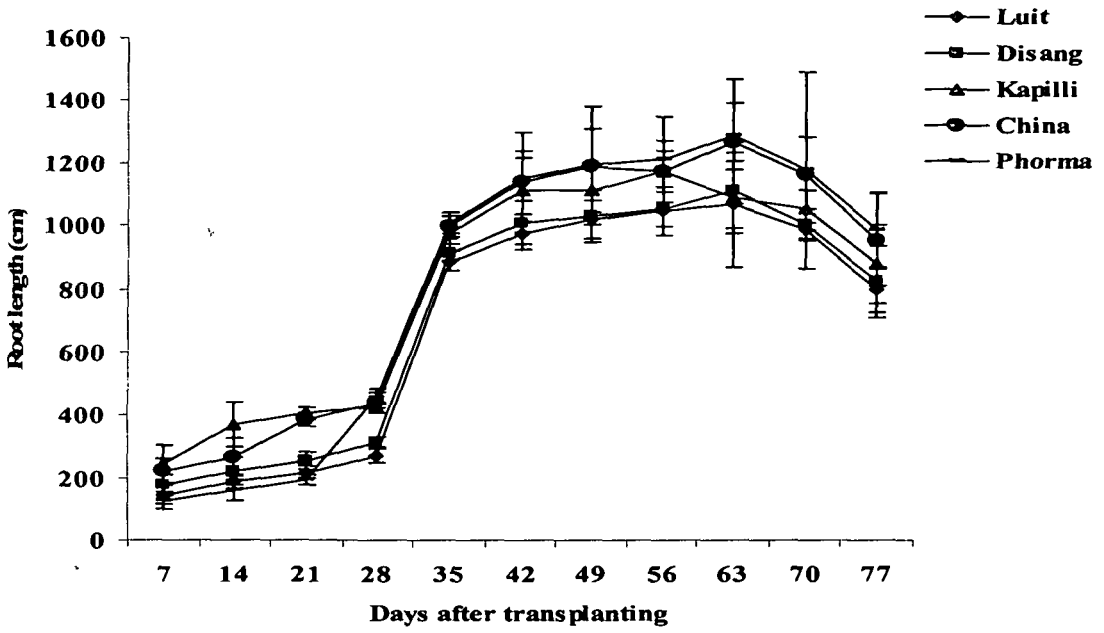


**Fig. 4.8. Root length (cm) of the rice varieties during autumn rice growing season. Vertical bars represent standard error of three replications.**

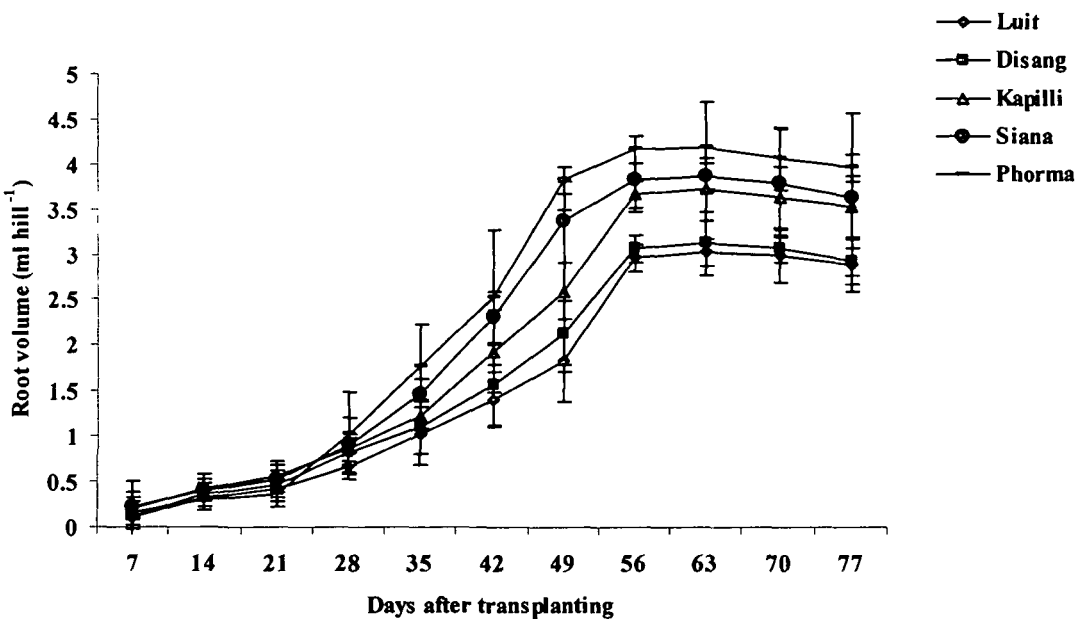


**Fig. 4.9. Root volume (ml hill$^{-1}$) of the rice varieties during autumn rice growing season. Vertical bars represent standard error of three replications.**

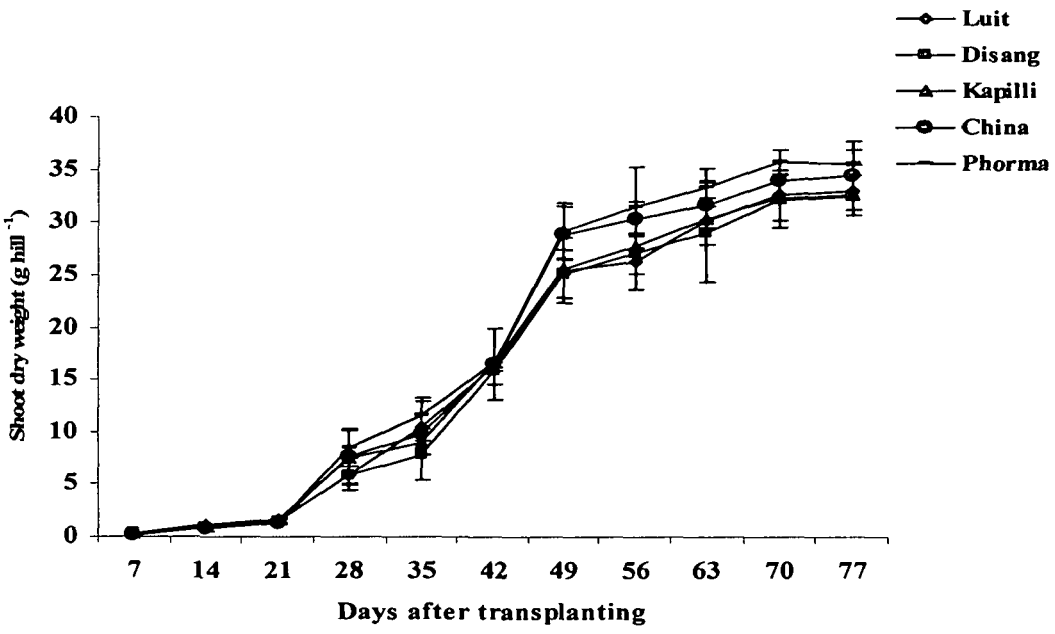


**Fig. 4.10. Shoot dry weight (g hill$^{-1}$) of the rice varieties during autumn rice growing season. Vertical bars represent standard error of three replications.**

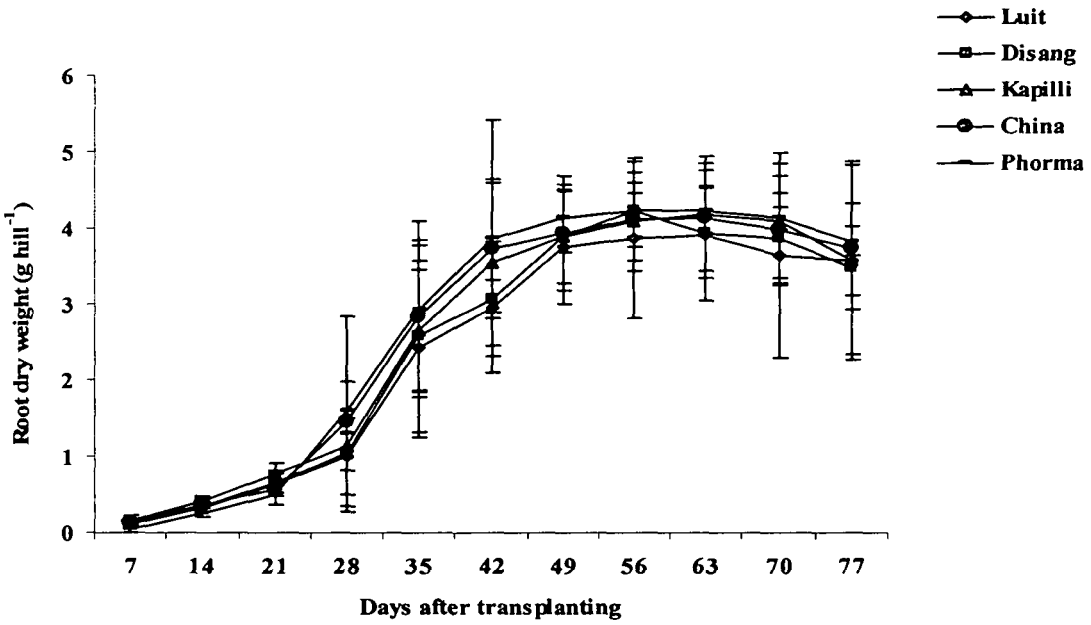


**Fig. 4.11. Root dry weight (g hill$^{-1}$) of the rice varieties during autumn rice growing season. Vertical bars represent standard error of three replications.**

### 4.1.12. Root volume (ml hill$^{-1}$)

Figure 4.9 represents the root volume (ml hill$^{-1}$) of the varieties. Root volume at initial stage (7 DAT) was low and gradually increased up to 63 DAT. At 63 DAT the recorded root volumes were 4.20 ml, 3.87 ml, 3.73 ml, 3.13 ml and 3.03 ml in varieties Phorma, Siana, Kapilli, Disang and Luit, respectively.

### 4.1.13. Shoot dry weight (g hill$^{-1}$)

Figure 4.10 represents the shoot dry weight (g hill$^{-1}$) of rice varieties. At 7 DAT shoot dry weight of rice varieties ranged from 0.15 g to 0.29 g. With increase in growth period the shoot dry weight increased and reached maximum values at 77 DAT. At 77 DAT shoot dry weights were 35.66 g, 34.39 g, 32.65 g, 32.54 g and 33.03 g in Phorma, Siana, Kapilli, Disang and Luit, respectively. Varieties Phorma and Siana recorded higher shoot dry weight compared to other varieties.

### 4.1.14. Root dry weight (g hill$^{-1}$)

Figure 4.11 represents the root dry weight (g hill$^{-1}$) of the varieties. Initially at 7 DAT root dry weight ranged from 0.04 g to 0.17 g. Root dry weight increased from 7 DAT onwards and showed higher values from active vegetative (35 DAT) growth stage onwards. Root dry weight declined at crop maturity stage. Varieties Phorma and Siana recorded higher root dry weight compared to other varieties.

### 4.1.15. Yield and yield attributing parameters

Table 4.3 shows the yield and yield attributing characteristics of rice varieties. The observed yields of rice varieties are 29.04q ha$^{-1}$, 28.10q ha$^{-1}$, 27.01q ha$^{-1}$, 26.47q

$ha^{-1}$ and 25.84q $ha^{-1}$ in Disang, Luit, Kapilli, Phorma and Siana, respectively. Varietal differences in yield are found to be significant. Luit showed significantly higher thousand grain weight (23.19 g) followed by Disang, Kapilli, Siana and Phorma. Phorma recorded higher panicle length (22.81cm) among the varieties. The varieties Phorma and Siana had higher number of panicles per square meter of land area. These two varieties also recorded higher grain sterility (Phorma 10.87% and Siana 9.33%).

The total variance explained by factors through factor analysis is indicated in Table 4.4. Three factors were extracted explaining a total of 88.40 % variation, which have eigenvalues greater than one. A principal factor matrix after varimax rotation for these 3 factors is given in Table 4.5. The values in the table indicate the contribution of each variable to the factors. For the purpose of interpretation only those factor loadings greater than 0.8 were considered important and these values are highlighted in bold in Table 4.5. Factor 1, accounted for about 65.30% of the variation. The variables; soil $NO_3^-$-N, leaf area, root length, root dry weight, and shoot dry weight have shown high loadings in factor 1 and are positively associated. Field water level is also highly loaded but it is negatively correlated to factor 1 and with other variables. The factor 1, can be regarded as "emission factor" since it included several variables which are found to be significantly related to $N_2O$ emission. Among the variables root dry weight followed by soil $NO_3^-$-N, shoot dry weight and field water level, have shown very high factor loadings (more than 0.95) and hence considered to be strongly associated with nitrous oxide emission i.e. factor 1. Factor 2 accounts for 11.98% of the variation and is regarded as "soil reaction factor" since soil pH is found to be highly loaded to this factor. Soil temperature is highly loaded to factor 3 which accounts for 11.10% of the variation and is regarded as "soil physical factor". Soil temperature is highly loaded to factor 3 which accounts for 11.29% of the variation and is regarded as "soil physical factor". Although soil pH and soil temperatures are strongly loaded in factor 2 and factor 3 respectively, the association between pH and soil temperature with other variables in factor 2 and 3 are not significant. The results are published in *J. Agron. Sustain. Develop.*, 2010, 30 (4), 733-742 (EDP Sciences).

**Table 4.1. Correlation of plant and soil parameters with nitrous oxide emission from rice varieties during autumn rice growing season.**

| Parameters | Correlation with nitrous oxide emission |
|---|---|
| Organic carbon (%) | $0.397^{NS}$ |
| Soil $NO_3^-$ - N (kg $ha^{-1}$) | 0.676* |
| Soil temperature (°C) | $-0.149^{NS}$ |
| Soil pH | $0.252^{NS}$ |
| Water level (cm) | -0.632* |
| Leaf area ($cm^2$ $hill^{-1}$) | 0.620* |
| Leaf number ($hill^{-1}$) | $0.496^{NS}$ |
| Root length (cm $hill^{-1}$) | $0.562^{*}$ |
| Root volume (ml $hill^{-1}$) | $0.485^{NS}$ |
| Root dry weight (g $hill^{-1}$) | $0.565^{*}$ |
| Shoot dry weight (g $hill^{-1}$) | $0.527^{*}$ |
| Plant height (cm) | $0.489^{NS}$ |
| Tiller number ($hill^{-1}$) | $0.427^{NS}$ |

*Correlation is significant at the 0.05 level of significance

**Correlation is significant at the 0.01 level of significance

$^{NS}$Non significant

**Table 4.2. Paddy growth parameters during autumn rice growing season. Values within the same column followed by same letters do not differ at $P<$ 0.05 level by Duncan's multiple range test.**

| Rice varieties/ parameters | Days after transplanting | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 7 | 14 | 21 | 28 | 35 | 42 | 49 | 56 | 63 | 70 | 77 |
| **Plant height (cm)** | | | | | | | | | | | |
| **Luit** | 26 23b | 36 03a | 44 60b | 50 59bc | 57 29c | 66 76b | 77 23b | 79 09c | 82 71c | 83 46c | 84 30c |
| **Disang** | 24 49b | 31 38b | 39 66c | 48 01c | 50 54d | 57 61d | 63 42c | 71 94d | 75 76d | 77 21d | 78 08d |
| **Kapilli** | 34 87a | 40 03a | 51 30a | 58 95a | 70 45a | 79 19a | 89 92a | 94 28b | 97 22b | 98 59b | 99 13b |
| **Siana** | 23 50b | 31 67b | 41 23c | 49 35bc | 56 72c | 64 97c | 76 56b | 81 23c | 83 95c | 86 30c | 86 99c |
| **Phorma** | 33 86a | 37 13a | 45 13b | 51 71b | 67 96b | 77 98a | 88 74a | 99 61a | 103 78a | 106 99a | 107 42a |
| **CD (5%)** | 2 90 | 3 91 | 3 24 | 2 52 | 0 53 | 1 67 | 1 57 | 2 97 | 2 52 | 3 35 | 3 52 |
| **Tiller number ($hill^{-1}$)** | | | | | | | | | | | |
| **Luit** | 3 33a | 6 33ab | 13 66a | 13 93a | 15 23ab | 15 43a | 15 57a | 15 77b | 14 43b | 11 93a | 10 29c |
| **Disang** | 3 67a | 7 33a | 13 67a | 14 50a | 15 77a | 16 03a | 16 16a | 16 23ab | 14 60ab | 12 28a | 10 91bc |
| **Kapilli** | 3 33a | 5 11bc | 12 00ab | 14 07a | 15 63a | 15 97a | 16 47a | 16 56ab | 14 67ab | 12 27a | 11 19ab |
| **Siana** | 2 89a | 4 33bc | 10 67b | 12 70b | 14 70b | 15 63a | 15 97a | 16 20ab | 14 53b | 11 99a | 10 93bc |
| **Phorma** | 3 22a | 4 00c | 10 00b | 12 83b | 15 13ab | 16 20a | 16 37a | 16 70a | 15 27a | 12 70a | 11 64a |
| **CD (5%)** | 1 56 | 2 03 | 2 69 | 0 69 | 0 68 | 0 77 | 0 84 | 0 79 | 0 67 | 0 82 | 0 68 |
| **Leaf number ($hill^{-1}$)** | | | | | | | | | | | |
| **Luit** | 15 33a | 23 67a | 40 67a | 47 60 | 47 96c | 49 73d | 51 17d | 52 13d | 47 37d | 39 49d | 31 43d |
| **Disang** | 14 33a | 25 67a | 37 00ab | 55 96 | 60 40a | 62 86c | 66 06c | 65 87c | 60 30c | 48 17c | 37 11c |
| **Kapilli** | 14 33a | 22 33a | 38 33a | 51 27 | 66 13b | 68 17b | 69 60b | 71 40b | 63 90b | 54 97b | 41 15b |
| **Siana** | 9 33b | 14 33b | 31 67b | 51 63 | 65 87b | 68 43b | 70 80ab | 71 83b | 65 27ab | 57 51a | 42 13ab |
| **Phorma** | 5 33c | 12 33c | 37 00ab | 50 40 | 62 90b | 70 67a | 72 73a | 74 40a | 67 47a | 55 26b | 43 21a |
| **CD (5%)** | 3 21 | 3 69 | 5 69 | 2 26 | 1 78 | 2 21 | 2 24 | 2 34 | 2 71 | 2 05 | 1 77 |

Table 4.3. Yield and yield attributing parameters of rice varieties and seasonal integrated nitrous oxide emission flux ($E_{sif}$) in autumn ecosystem. Values within the same column followed by same letters do not differ at $P< 0.05$ level by Duncan's multiple range test.

| Rice varieties/ parameters | Panicle square meter$^{-1}$ | Panicle length (cm) | Sterility (%) | Thousand grain weight (g) | Yield (q ha$^{-1}$) | $E_{sif}$ (mg $N_2O$-N m$^{-2}$) |
|---|---|---|---|---|---|---|
| Luit | 244.66 b | 21.77 b | 8.07 d | 23.19 a | 28.10 b | 99.97 c |
| Disang | 243.00 b | 20.65 c | 7.65 e | 23.02 b | 29.04 a | 77.14 e |
| Kapilli | 245.00 b | 20.83 c | 8.43 c | 22.87 b | 27.01 c | 84.68 d |
| Siana | 250.33 a | 20.54 c | 9.33 b | 20.78 c | 26.47 d | 139.19 b |
| Phorma | 253.00 a | 22.81 a | 10.87 a | 20.12 d | 25.84 e | 150.30 a |

**Table 4.4. Total variance explained for each factor (autumn rice ecosystem).**

| Component | % of Variance | Cumulative % |
|---|---|---|
| 1 | 65.305 | 65.305 |
| 2 | 11.989 | 77.294 |
| 3 | 11.106 | 88.401 |
| 4 | 6.362 | 94.763 |
| 5 | 3.904 | 98.667 |
| 6 | 0.794 | 99.461 |
| 7 | 0.430 | 99.891 |
| 8 | 8.675E-02 | 99.978 |
| 9 | 2.230E-02 | 100.000 |
| 10 | 1.162E-05 | 100.000 |

**Table 4.5. Principal factor matrix after varimax rotation (autumn rice ecosystem).**

| Variables | Factor | | | Proportion of each variable's variance explained by the underlying factors |
|---|---|---|---|---|
| | 1 | 2 | 3 | |
| $N_2O$ flux | 0.646 | 0.238 | | 0.482 |
| Soil $NO_3^-$-N | **0.961** | | | 0.929 |
| Soil organic carbon | 0.643 | 0.423 | 0.482 | 0.825 |
| Field water | **-0.966** | | | 0.943 |
| Leaf area | **0.874** | 0.446 | | 0.963 |
| Root length | **0.939** | 0.291 | | 0.967 |
| Rood dry weight | **0.977** | 0.141 | | 0.976 |
| Shoot dry weight | **0.955** | -0.143 | | 0.938 |
| Soil temperature | -0.171 | -0.150 | **0.925** | 0.908 |
| Soil pH | | **0.944** | -0.122 | 0.909 |

Numbers in bold are those with factor loadings greater than 0.80.

## 4.2. Nitrous oxide emission estimation from monsoon rice (*Sali*) ecosystem and plant and soil parameters associated with the emission

### 4.2.1. Meteorological parameters

Meteorological parameters recorded during experimental period are presented in Figure 3.3. During experimental period the average minimum and maximum weekly temperature ranged from 12.07°C to 36.17°C. Maximum average temperature was recorded in August and minimum during December 2006. Maximum average rainfall of 12.17 mm was recorded in the month of August and there was no rainfall from November onwards.

### 4.2.2. Nitrous oxide flux (μg $N_2O$-N $m^{-2}$ $h^{-1}$)

The $N_2O$ fluxes recorded from the varieties ranged from 0.90 μg $N_2O$-N $m^{-2}$ $h^{-1}$ to 157.60 μg $N_2O$-N $m^{-2}$ $h^{-1}$ (Fig. 4.12). $N_2O$ fluxes at the time of transplanting (0 DAT) were low. Gradually flux rates increased from 7 DAT onwards and showed emission peaks at 35, 56 and 84 DAT which corresponds to active vegetative and reproductive stages of the varieties. The rate of emission declined at crop maturity and harvest. The $E_{sif}$ values from rice varieties are, Basmuthi (189.46 mg $N_2O$-N $m^{-2}$), Bogajoha (174.80 mg $N_2O$-N $m^{-2}$), Lalkalamdani (168.93 mg $N_2O$-N $m^{-2}$), Choimora(160.71 mg $N_2O$-N $m^{-2}$), Rashmisali (158.30 mg $N_2O$-N $m^{-2}$), Profulla (143.30 mg $N_2O$-N $m^{-2}$), Moniram (141.17 mg $N_2O$-N $m^{-2}$), Mahsuri (140.54 mg $N_2O$-N $m^{-2}$), Kushal (129.39 mg $N_2O$-N $m^{-2}$) and Gitesh (121.63 mg $N_2O$-N $m^{-2}$). Rice variety Basmuthi recorded significantly higher seasonal $N_2O$ emission and rice variety Gitesh followed by kushal recorded the lowest. Calculated $E_{sif}$ values of the traditional rice varieties differed significantly from high yielding varieties (Table 4.10).

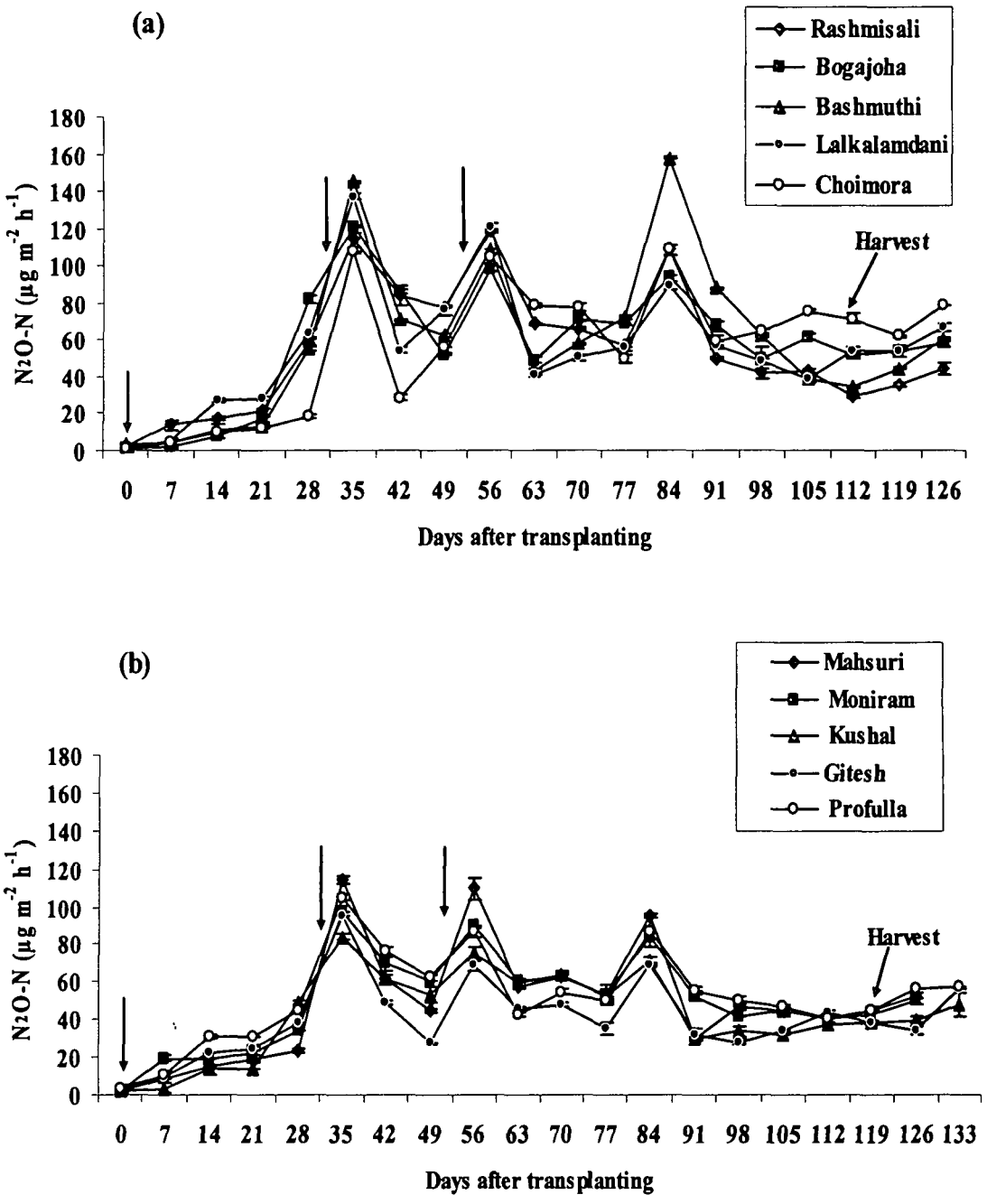


**Fig. 4.12. Nitrous oxide fluxes $N_2O$-N (µg $m^{-2}$ $h^{-1}$) from traditional rice varieties (a), and from high yielding rice varieties (b) in monsoon rice ecosystem. Vertical bars represent standard error of three replications. The arrows indicate the time of application of fertilizer and day of harvest.**

### 4.2.7. Soil pH

Figure 4.16 represents the soil pH of the experimental field. Soil pH of the experimental field ranged from 5.05- 6.25. The observed correlation between $N_2O$ emission and soil pH in the present study is not significant (Table 4.6).

### 4.2.7. Plant height (cm)

Table 4.7 represents the plant height of rice varieties. Plant height at initial growth period (7 DAT) ranged from 35.13 cm - 48.43 cm in the varieties, up to 77 DAT the rate of increase in plant heights were found to be high.

### 4.2.8. Tiller number ($hill^{-1}$)

Table 4.7 represents the tiller number of rice varieties. Number of tillers per hill increased up to panicle initiation stage and declined at crop maturity stage. There was variation in tiller number per hill among the varieties. The observed correlation between $N_2O$ emission and tiller number in the present study is significant (Table 4.6).

### 4.2.9. Leaf number ($hill^{-1}$)

Table 4.8 represents the leaf number $hill^{-1}$ of rice varieties. Leaf number at 7 DAT varied from 24-38 $hill^{-1}$. Leaf number increased in all rice varieties up to panicle initiation (70 DAT). At this stage traditional rice variety Basmuthi, Bogajoha and Choimora showed higher leaf number $hill^{-1}$. Leaf number started to decline after panicle initiation till crop harvest. Variations in leaf number within the rice varieties were recorded.

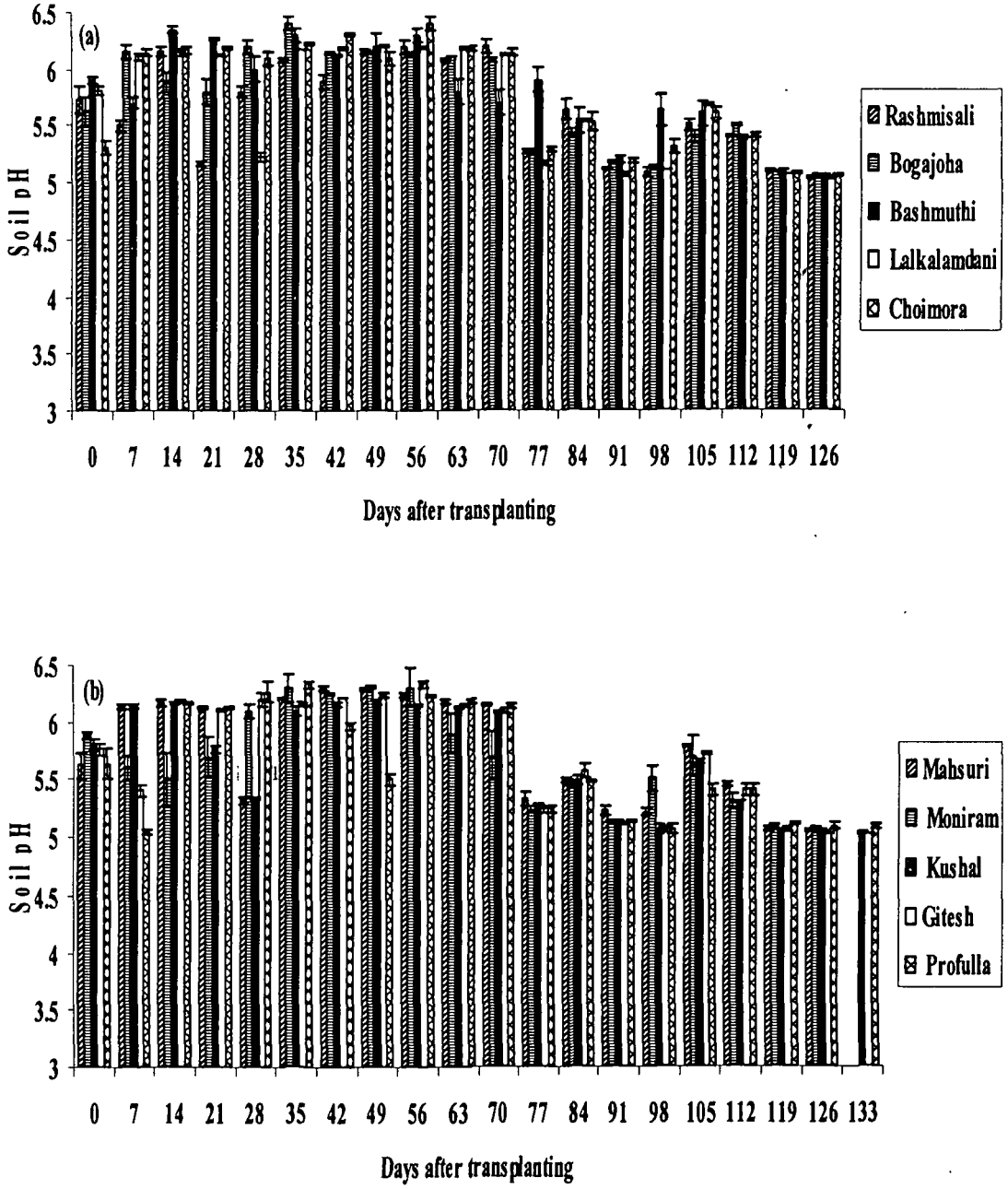


**Fig. 4.16. Soil pH of the experimental field grown with traditional rice varieties (a), and grown with high yielding rice varieties (b) during monsoon rice growing season. Vertical bars represent standard error of three replications.**

### 4.2.10. Leaf area ($cm^2$ $hill^{-1}$)

The leaf area of rice varieties initially (7 DAT) ranged from 110.49 $cm^2$ to 282.64 $cm^2$ (Table 4.8). Leaf area gradually increased from 7 DAT onwards up to 70 DAT and started to decline thereafter. Higher leaf area values were observed in traditional rice varieties Basmuthi, Rashmisali and Bogajoha at 70 DAT. A significant correlation of $N_2O$ emission and leaf area is reported in the present study (Table 4.6).

### 4.2.11. Root length (cm $hill^{-1}$)

Figure 4.17 represents the root length (cm $hill^{-1}$) of the varieties. The recorded root length was from 27.20 cm to 69.60 cm in the varieties. The root length at 7 DAT increased gradually till crop ripening stage and then declined. The varieties recorded different root length among them. The traditional rice varieties showed higher root length at different growth stages.

### 4.2.12. Root volume (ml $hill^{-1}$)

Root volume gradually started to increase from 7 DAT up to ripening stage (Figure 4.18). The recorded root volumes in traditional varieties are higher compared to high yielding varieties. At 91 DAT traditional rice varieties, Basmuthi, Bogajoha, Choimora, Rashmisali and Lalkalamdani showed root volumes of 22.86ml, 22.16ml, 21.80ml, 20.53ml and 20.00ml, respectively and then root volumes decreased after 91 DAT.

### 4.2.13. Shoot dry weight (g $hill^{-1}$)

Table 4.9 represents the shoot dry weight (g $hill^{-1}$) of the varieties. With increase in plant growth shoot dry weight increased gradually from 7 DAT onwards. Shoot dry weight of rice varieties reached maximum at 98 DAT. The recorded shoot

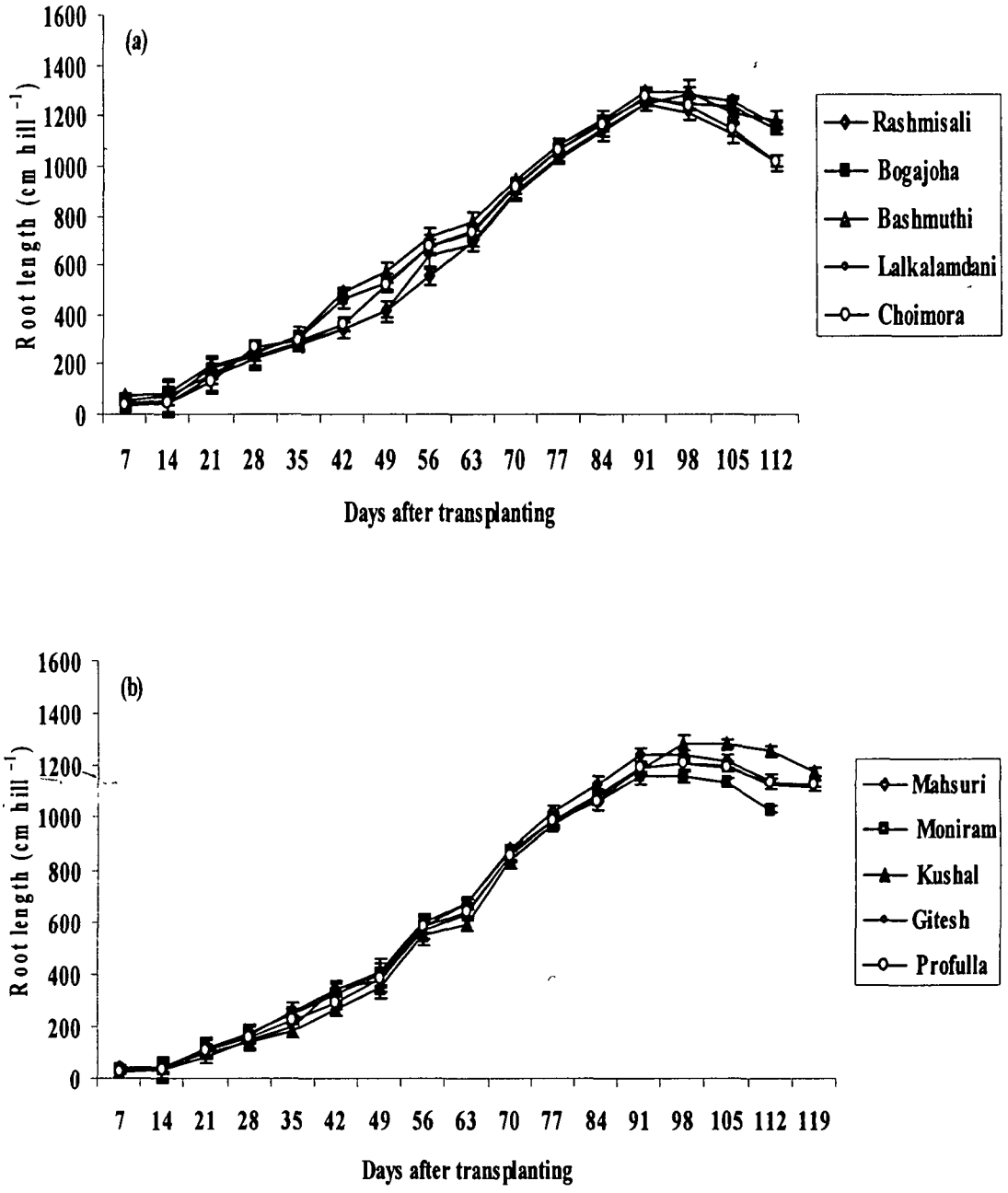


**Fig. 4.17. Root length (cm) of traditional rice varieties (a), and high yielding rice varieties (b) during monsoon rice growing season. Vertical bars represent standard error of three replications.**

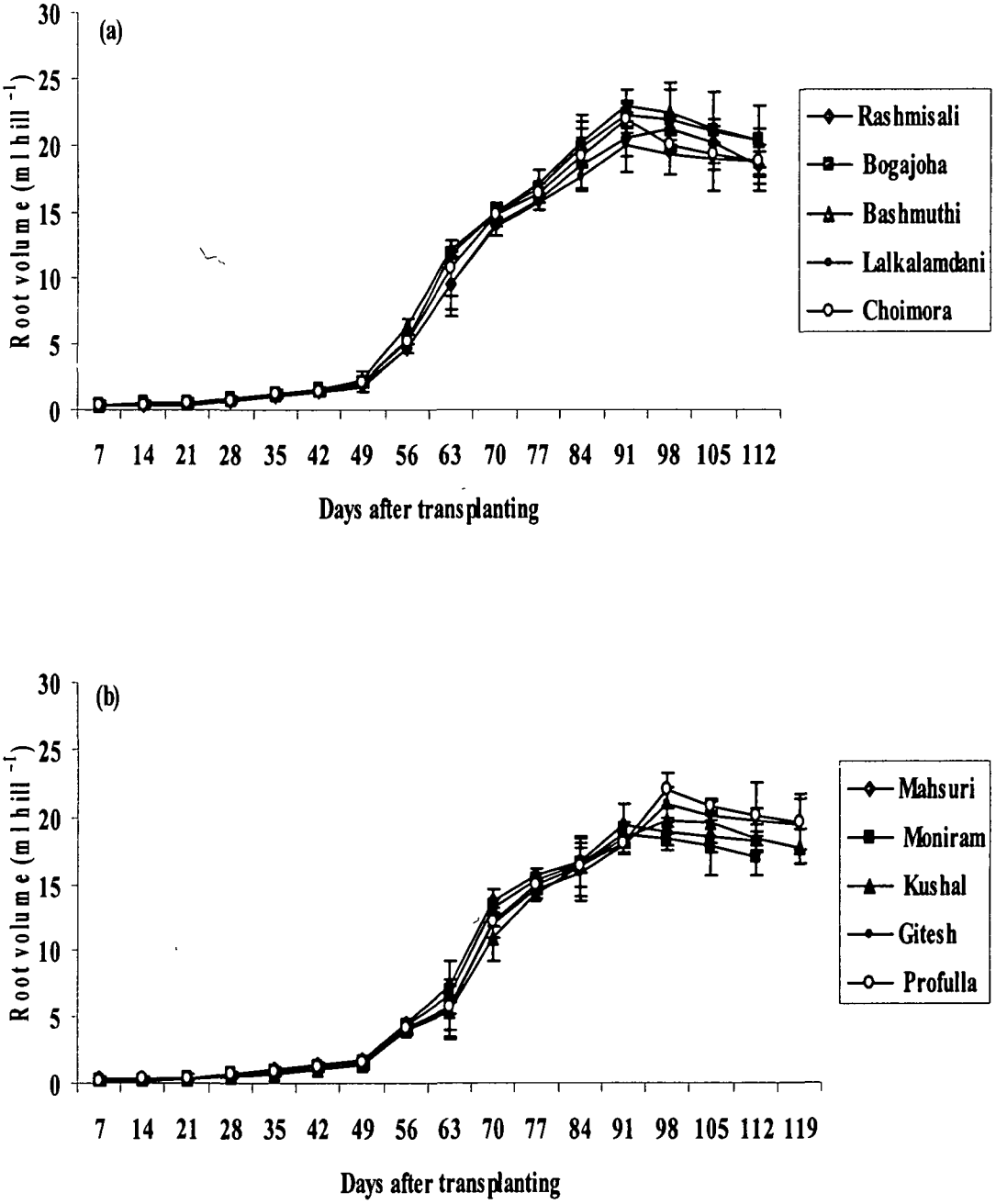


**Fig. 4.18. Root volume (ml hill$^{-1}$) of traditional rice varieties (a), and high yielding rice varieties (b) during monsoon rice growing season. Vertical bars represent standard error of three replications.**

dry weights of traditional rice varieties are higher compared to high yielding varieties at different growth stages. Although there were varietal differences in shoot dry weights but shoot dry weights did not exhibit significant relationship with $N_2O$ emission.

### 4.2.14. Root dry weight (g hill$^{-1}$)

Root dry weights increased gradually from 7 DAT up to 28 DAT (Table 4.9). High rate of increase in root dry weights were observed from 28 DAT onwards up to 91 DAT. Root dry weights declined at crop maturity stage. Root dry weights of traditional varieties were higher at different growth stages. The root dry weights exhibited significant relationship with $N_2O$ emission in the present study (Table 4.6).

### 4.2.15. Yield and yield attributing parameters

Data recorded on yield and yield attributing characteristics of rice varieties are presented in Table 4.10. The rice varieties Gitesh and Kushal recorded higher yield of 38.20q ha$^{-1}$ and 37.26q ha$^{-1}$, respectively among the varieties. High yielding variety Gitesh followed by Kushal had higher thousand grain weights (20.76g and 20.23g, respectively). The panicle lengths of varieties Profulla, Basmuthi were higher than the other varieties. The number of panicles per square meter was recorded to be high in varieties Mahsuri, Gitesh and Kushal. There was significant variation in yield and yield attributing characteristics within the varieties. The results are published in *J. Physiol. Mol. Biol. Plants.*, 2010, 16 (1): 79-91, (Springer).

**Table 4.6. Correlation of plant and soil parameters with nitrous oxide emission from rice varieties during monsoon rice growing season.**

| Parameters | Correlation with nitrous oxide emission |
|---|---|
| Organic carbon (%) | 0.576 * |
| Soil $NO_3^-$ - N (kg $ha^{-1}$) | 0.581 * |
| Soil temperature ($^oC$) | 0.405 $^{NS}$ |
| Soil pH | 0.214 $^{NS}$ |
| Water level (cm) | -0.049 $^{NS}$ |
| Leaf area ($cm^2$ $hill^{-1}$) | 0.590* |
| Leaf number($hill^{-1}$) | 0.552* |
| Root length (cm $hill^{-1}$) | 0.257 $^{NS}$ |
| Root volume (ml $hill^{-1}$) | 0.118 $^{NS}$ |
| Root dry weight (g $hill^{-1}$) | 0.586* |
| Shoot dry weight (g $hill^{-1}$) | 0.442 |
| Plant height (cm) | 0.363 $^{NS}$ |
| Tiller number ($hill^{-1}$) | 0.657** |

*Correlation is significant at the 0.05 level of significance

**Correlation is significant at the 0.01 level of significance

$^{NS}$Non significant

**Table 4.7. Variations in plant height and tiller number within ten rice varieties in monsoon rice ecosystem. In each column, values with the similar letters are not significantly different at $P<0.05$ level by Duncan's multiple range test.**

| | Days after transplanting | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 7 | 14 | 21 | 28 | 35 | 42 | 49 | 56 | 63 | 70 | 77 | 84 | 91 | 98 | 105 | 112 | 119 |
| **Plant height (cm)** | | | | | | | | | | | | | | | | | |
| V1 | 48 43a | 62 02a | 71 76a | 76 92a | 82 08a | 85 90a | 89 32a | 94 36a | 99 43a | 105 82a | 116 16a | 118 63a | 121 90a | 123 27a | 124 56a | 124 97a | |
| V2 | 44 97ab | 60 10a | 62 85c | 67 39de | 72 73c | 76 44cd | 80 80d | 85 56c | 90 93bc | 96 57c | 101 98c | 104 23e | 109 59c | 113 33c | 113 95c | 114 07c | |
| V3 | 47 36a | 63 56a | 68 41b | 72 93b | 76 88b | 80 61b | 83 79b | 88 80b | 93 39b | 100 06b | 104 06b | 106 62d | 109 13c | 110 11e | 110 93e | 111 04e | |
| V4 | 44 88ab | 61 65a | 65 02c | 70 72c | 75 99b | 80 13b | 83 27bc | 87 81b | 92 51bc | 97 77bc | 104 79b | 110 80b | 114 18b | 115 32b | 115 93b | 115 56b | |
| V5 | 45 02ab | 61 06a | 64 24c | 68 81d | 73 78c | 77 75c | 81 13cd | 85 73c | 90 22c | 94 88c | 101 82c | 108 47c | 111 38bc | 112 42cd | 112 99cd | 113 01cd | |
| V6 | 42 99bc | 53 95b | 62 92c | 66 34e | 70 47d | 74 80d | 77 70e | 82 69d | 86 92d | 90 80d | 95 37d | 107 12d | 109 72c | 111 28de | 111 89de | 112 08de | |
| V7 | 42 75bc | 49 55c | 55 58d | 58 36f | 63 98e | 67 90e | 70 72f | 75 34e | 79 82e | 84 13e | 88 95e | 94 29f | 95 69d | 96 76f | 97 68f | 97 83f | |
| V8 | 37 21de | 45 94cd | 54 73d | 56 68f | 62 92e | 66 24e | 69 40f | 71 25f | 72 59f | 74 18f | 75 30h | 76 74i | 77 95f | 79 09i | 80 33i | 80 82i | 81 25c |
| V9 | 39 39cd | 46 12cd | 53 84d | 58 01f | 63 97e | 66 13e | 71 66f | 76 18e | 81 40e | 83 49e | 86 52f | 90 80g | 92 32d | 93 96g | 94 73g | 95 51g | 95 69a |
| V10 | 35 14e | 44 66d | 50 95e | 53 19g | 57 84f | 62 19f | 66 37g | 70 40g | 74 61f | 77 07f | 80 10g | 82 43h | 84 04e | 85 75h | 86 33h | 86 45h | 86 81b |
| CD-5% | 3 60 | 3 93 | 2 09 | 1 79 | 2 04 | 1 99 | 2 20 | 1 88 | 2 43 | 3 02 | 1 45 | 1 32 | 3 51 | 1 37 | 1 23 | 1 12 | 0 32 |
| **Tiller number (hill $^{-1}$)** | | | | | | | | | | | | | | | | | |
| V1 | 5 70bcd | 10 23ab | 11 70bc | 12 07de | 13 13c | 14 33c | 14 67cde | 15 20bc | 15 30bc | 15 43cd | 14 40cd | 13 40bcd | 12 20cde | 10 27f | 9 63e | 9 47d | |
| V2 | 6 43ab | 10 67ab | 12 33b | 13 17bc | 13 53bc | 15 00b | 15 23b | 15 63b | 15 83b | 16 30ab | 15 20abc | 13 90abc | 12 73ab | 11 83a | 11 47a | 10 53abc | |
| V3 | 6 77a | 11 00a | 13 17a | 14 00a | 14 57a | 15 77a | 15 97a | 16 47a | 16 67a | 16 83a | 15 33abc | 13 87abc | 12 63abc | 11 90a | 11 27ab | 10 30abc | |
| V4 | 6 37ab | 10 20ab | 11 63bcd | 12 60cd | 13 10c | 14 37c | 14 70cde | 15 13bc | 15 30bc | 15 43cd | 15 53ab | 14 30a | 12 20cde | 11 53abc | 11 03ab | 10 80a | |
| V5 | 6 60ab | 10 00bc | 12 37b | 13 33b | 13 77b | 14 57bc | 14 87bcd | 15 23bc | 15 40bc | 15 57cd | 15 60a | 13 10d | 11 87e | 10 80de | 10 20d | 9 93bcd | |
| V6 | 5 93abc | 10 27ab | 11 33cde | 12 93bc | 13 77b | 14 60bc | 14 93bc | 15 43b | 15 73b | 15 87bc | 15 97a | 14 57a | 12 33bcde | 11 57ab | 10 83b | 10 30abc | |
| V7 | 6 30ab | 10 43ab | 12 23b | 12 90bc | 13 50bc | 14 23c | 14 63cde | 15 20bc | 15 47bc | 15 63cd | 14 60bcd | 13 17cd | 12 00de | 11 03cde | 10 77bc | 10 37abc | |
| V8 | 5 03cd | 8 23e | 10 77e | 11 63e | 12 53d | 13 03d | 13 73f | 14 03e | 14 23d | 14 80e | 13 83d | 12 33e | 11 23f | 10 63ef | 10 33cd | 9 90bcd | 9 40b |
| V9 | 4 90d | 8 77de | 10 83d | 11 83e | 12 57d | 13 47d | 14 40de | 14 87cd | 15 07c | 15 23de | 15 40ab | 14 27a | 13 07a | 11 20bcd | 10 90b | 9 80cd | 9 40b |
| V10 | 5 23cd | 9 20cd | 10 90cde | 11 77e | 12 40d | 13 40d | 14 27e | 14 63d | 14 93c | 15 17de | 15 27abc | 14 07ab | 12 43bcd | 11 13bcde | 11 03ab | 10 63ab | 10 10a |
| CD-5% | 0 88 | 0 84 | 0 75 | 0 67 | 0 50 | 0 50 | 0 45 | 0 47 | 0 52 | 0 56 | 0 86 | 0 70 | 0 46 | 0 48 | 0 47 | 0 66 | 0 43 |

($V_1$): Rashmisali, ($V_2$): Bogajoha, ($V_3$): Basmuthi, ($V_4$): Lalkalamdani, ($V_5$): Choimora, ($V_6$): Mahsuri, ($V_7$): Moniram, ($V_8$): Kushal, ($V_9$): Gitesh, ($V_{10}$): Profulla

**Table 4.8. Variations in leaf number and leaf area within ten rice varieties in monsoon rice ecosystem. In each column, values with the similar letters are not significantly different at $P<0.05$ level by Duncan's multiple range test.**

| | Days after transplanting | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 7 | 14 | 21 | 28 | 35 | 42 | 49 | 56 | 63 | 70 | 77 | 84 | 91 | 98 | 105 | 112 | 119 |
| **Leaf number (hill $^{-1}$)** | | | | | | | | | | | | | | | | | |
| V1 | 30 17cd | 52 70c | 59 43c | 65 13c | 68 67c | 73 73c | 75 70c | 78 70c | 80 27b | 77 93c | 68 27d | 50 83d | 36 33d | 31 80de | 28 10de | 25 97bc | |
| V2 | 34 90ab | 58 67b | 62 87b | 67 53b | 72 03b | 77 20b | 79 53b | 81 90b | 82 77b | 84 93b | 75 00bc | 66 07b | 49 37c | 29 40ef | 25 87f | 24 20d | |
| V3 | 36 97a | 62 00a | 66 57a | 71 13a | 76 17a | 81 53a | 83 80a | 88 43a | 89 37a | 91 10a | 82 10a | 68 10b | 47 37c | 36 30c | 29 53cd | 27 07abc | |
| V4 | 36 67ab | 44 97e | 58 00cd | 62 30d | 65 90d | 70 00d | 72 57d | 75 07d | 76 10cd | 77 80c | 74 70bc | 65 87b | 55 87b | 40 43b | 32 20b | 28 50a | |
| V5 | 35 50ab | 41 20f | 55 10e | 67 60b | 70 77b | 74 83c | 77 30c | 80 07bc | 80 83b | 82 90b | 83 37a | 77 33a | 60 07a | 48 40a | 37 13a | 26 73bc | |
| V6 | 32 80bc | 44 53e | 52 57f | 61 43d | 65 50d | 69 90d | 72 47d | 75 30d | 77 83c | 78 13c | 75 73b | 68 67b | 56 63b | 33 33d | 29 53cd | 27 30ab | |
| V7 | 37 77a | 48 60d | 56 63de | 61 07d | 64 37de | 68 40d | 70 90de | 73 67de | 74 20de | 75 50de | 75 43b | 67 60b | 54 07b | 34 53cd | 29 73cd | 27 03abc | |
| V8 | 28 30de | 39 77f | 45 87gh | 51 27g | 55 90g | 60 07f | 62 73f | 65 30f | 66 60f | 59 30e | 45 90e | 37 50e | 31 50e | 29 00f | 26 83ef | 25 40cd | 23 27a |
| V9 | 23 53f | 37 80f | 46 83g | 57 53e | 62 30f | 65 63e | 68 90e | 71 63e | 72 80e | 74 27d | 71 97c | 62 17c | 46 57c | 32 13de | 30 00cd | 26 50bc | 23 27a |
| V10 | 25 63ef | 34 03g | 43 57h | 55 13f | 63 67ef | 68 07d | 70 53de | 73 77de | 74 20de | 75 97cd | 76 07b | 67 87b | 54 87b | 41 80b | 30 97bc | 25 77bcd | 23 67a |
| CD (5%) | 3 61 | 3 28 | 2 36 | 2 32 | 1 68 | 2 28 | 2 08 | 2 27 | 2 40 | 3 05 | 3 05 | 2 56 | 3 10 | 2 65 | 1 90 | 1 54 | 1 08 |
| **Leaf area (cm $^{-2}$ hill $^{-1}$)** | | | | | | | | | | | | | | | | | |
| V1 | 206 87d | 242 08c | 310 11e | 364 20f | 612 59b | 724 66c | 771 92cd | 943 02b | 1062 04a | 1036 22a | 998 76b | 934 85abc | 817 22a | 737 20a | 613 15d | 590 23c | |
| V2 | 214 65c | 282 80b | 327 50d | 361 95f | 705 35a | 824 30a | 911 19a | 972 85a | 1015 44c | 1028 44ab | 1002 31b | 936 87ab | 823 22a | 634 58bc | 526 30h | 511 56de | |
| V3 | 246 27b | 320 56a | 455 82a | 530 83a | 607 50b | 755 22b | 885 85a | 981 00a | 1025 64b | 1037 60a | 1031 45a | 950 78a | 829 77a | 629 79bc | 548 51g | 528 90de | |
| V4 | 147 97f | 237 50c | 412 33b | 480 03c | 515 04cd | 649 37e | 789 34bc | 892 46c | 988 62d | 985 52c | 977 24cd | 911 13de | 777 57d | 620 57bc | 515 18ı | 499 82e | |
| V5 | 282 64a | 286 53b | 448 61a | 501 82b | 528 16c | 694 82d | 811 65b | 945 89b | 994 09d | 1023 45b | 1026 02a | 915 10cd | 790 87bcd | 646 87b | 557 04f | 532 30d | |
| V6 | 193 29e | 238 56c | 362 07c | 423 59d | 485 47d | 592 53f | 749 28de | 831 73d | 946 84e | 986 94c | 981 13c | 947 16a | 800 89b | 749 12a | 699 17b | 637 90b | |
| V7 | 197 54e | 232 72cd | 356 64c | 435 90d | 527 62c | 585 38f | 745 90def | 814 89e | 887 40f | 971 13d | 970 93d | 922 81bcd | 797 18bc | 721 16a | 714 83a | 699 88a | |
| V8 | 129 29g | 206 55d | 293 22f | 394 96e | 420 28e | 556 86g | 714 74f | 797 15f | 881 29f | 956 69e | 958 93e | 891 19e | 785 18cd | 742 92a | 716 35a | 694 22a | 663 03a |
| V9 | 111 44h | 151 43e | 180 92h | 324 51g | 390 28e | 586 06f | 721 26ef | 757 45g | 833 45h | 831 34f | 794 22g | 715 16f | 677 22f | 611 99c | 594 17e | 564 57c | 535 65c |
| V10 | 110 49h | 174 48e | 239 90g | 381 61e | 412 97e | 526 89h | 677 69g | 764 67g | 850 53g | 951 54e | 947 79f | 890 90e | 751 24e | 729 58a | 689 53c | 651 47b | 611 45b |
| CD (5%) | 7 69 | 26 83 | 12 56 | 14 44 | 34 64 | 9 45 | 31 85 | 8 46 | 8 60 | 9 29 | 7 18 | 19 58 | 13 18 | 27 33 | 8 39 | 29 08 | 3 64 |

($V_1$): Rashmisali, ($V_2$): Bogajoha, ($V_3$): Basmuthi, ($V_4$): Lalkalamdani, ($V_5$): Choimora, ($V_6$): Mahsuri, ($V_7$): Moniram, ($V_8$): Kushal, ($V_9$): Gitesh, ($V_{10}$): Profulla

**Table 4.9. Variations in shoot dry weight and root dry weight within ten rice varieties in monsoon rice ecosystem. In each column, values with the similar letters are not significantly different at $P<0.05$ level by Duncan's multiple range test.**

| | Days after transplanting | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 7 | 14 | 21 | 28 | 35 | 42 | 49 | 56 | 63 | 70 | 77 | 84 | 91 | 98 | 105 | 112 | 119 |
| **Shoot dry weight (g hill$^{-1}$)** | | | | | | | | | | | | | | | | | |
| V1 | 0 74c | 0 85e | 1 60cd | 3 64b | 15 81b | 17 27b | 19 19c | 28 26b | 30 28b | 31 24b | 32 25c | 33 22b | 34 06c | 34 44b | 32 20b | 30 27b | |
| V2 | 0 80b | 1 28bc | 2 05ab | 3 27bc | 13 53c | 14 36c | 17 26d | 29 25a | 31 47a | 33 19a | 33 67b | 34 87a | 35 12b | 35 44a | 34 18a | 28 32c | |
| V3 | 0 87a | 1 32b | 1 95bc | 3 56b | 12 64d | 14 40c | 16 82d | 26 32c | 30 32b | 33 96a | 34 91a | 34 99a | 35 77a | 35 97a | 33 43a | 31 33a | |
| V4 | 0 74c | 1 22bc | 1 93bc | 4 73a | 16 41a | 18 52a | 21 54a | 29 30a | 30 59b | 31 43b | 32 19c | 33 44b | 33 45c | 33 53c | 31 50b | 29 62b | |
| V5 | 0 80b | 1 95a | 2 02ab | 4 38a | 15 36b | 17 35b | 21 37a | 28 30b | 29 47c | 30 54b | 32 58c | 33 08b | 33 91c | 34 12bc | 33 92a | 31 58a | |
| V6 | 0 72c | 1 16bcd | 1 94bc | 3 31bc | 7 20h | 18 35a | 20 36b | 25 36d | 27 30d | 27 84c | 29 21d | 29 39c | 29 79d | 29 81de | 28 01d | 26 22d | |
| V7 | 0 72c | 1 06cde | 1 82bc | 2 74de | 11 33e | 12 23e | 13 45f | 23 41e | 26 23e | 27 26c | 28 74d | 29 76c | 29 51d | 29 34ef | 28 88c | 27 55c | |
| V8 | 0 62d | 1 05cde | 1 93bc | 2 46e | 12 45d | 13 47d | 15 47e | 22 27f | 23 45f | 25 71d | 27 35e | 27 73d | 28 22e | 28 88f | 25 61e | 24 22e | 23 39b |
| V9 | 0 58e | 1 40b | 2 35a | 3 04cd | 10 19f | 11 41f | 12 34g | 21 40g | 22 52g | 24 40e | 25 91f | 26 78e | 27 83e | 26 40g | 25 67e | 24 65e | 24 24a |
| V10 | 0 60de | 0 94de | 1 47d | 2 25e | 9 46g | 11 45f | 13 40f | 17 53h | 22 42g | 24 36e | 26 06f | 27 37de | 29 23d | 30 15d | 28 68cd | 27 81c | 24 76a |
| CD (5%) | 0 02 | 0 23 | 0 32 | 0 48 | 0 56 | 0 33 | 0 74 | 0 38 | 0 35 | 0 91 | 0 84 | 0 82 | 0 60 | 0 65 | 0 81 | 0 92 | 0 64 |
| **Root dry weight (g hill$^{-1}$)** | | | | | | | | | | | | | | | | | |
| V1 | 0 17ab | 0 39d | 0 68d | 1 46cd | 3 76b | 4 13d | 4 77cd | 5 16de | 5 58b | 5 86d | 6 14c | 6 35c | 6 36c | 5 61e | 4 08h | 3 39f | |
| V2 | 0 21ab | 0 43b | 0 71c | 1 51abc | 3 81ab | 4 25bc | 4 82c | 5 26bc | 5 68b | 6 19bc | 6 43b | 6 62b | 6 64b | 5 78d | 4 18g | 3 90d | |
| V3 | 0 24a | 0 47a | 0 79a | 1 57a | 2 85e | 4 37a | 4 99a | 5 38a | 5 83a | 6 29a | 6 55a | 6 82a | 6 86a | 4 88f | 4 32f | 3 71e | |
| V4 | 0 20ab | 0 41c | 0 70c | 1 49bcd | 3 99a | 4 24c | 4 74d | 5 19cd | 5 62b | 6 15c | 6 42b | 6 54b | 6 59b | 6 60a | 5 12c | 4 51b | |
| V5 | 0 22ab | 0 46a | 0 76b | 1 54ab | 3 77b | 4 30b | 4 88b | 5 32ab | 5 79a | 6 25ab | 6 38b | 6 56b | 6 62b | 5 81cd | 4 23g | 3 65e | |
| V6 | 0 13ab | 0 34e | 0 64ef | 1 37e | 2 64f | 4 07e | 4 60e | 5 03f | 5 33c | 5 41fg | 5 62e | 5 83d | 5 91e | 4 45g | 3 83i | 3 19g | |
| V7 | 0 12ab | 0 31f | 0 62f | 1 30f | 3 24d | 4 23c | 4 54f | 5 17de | 5 32c | 5 69e | 5 74d | 5 84d | 5 86e | 5 88b | 5 53b | 4 63b | |
| V8 | 0 05b | 0 25h | 0 55h | 0 99g | 2 39g | 3 67g | 4 31g | 4 63g | 5 17d | 5 35gh | 5 44f | 5 65e | 5 85ef | 5 86bc | 5 34c | 4 86a | 4 15a |
| V9 | 0 28a | 0 29g | 0 58g | 1 25f | 3 54c | 3 75f | 4 12i | 5 14de | 5 19d | 5 31h | 5 49f | 5 70e | 5 78f | 5 82cd | 5 23d | 4 57b | 3 43b |
| V10 | 0 16ab | 0 38d | 0 65e | 1 43d | 3 55c | 4 10de | 4 24h | 5 09ef | 5 35c | 5 46f | 5 68de | 5 87d | 6 05d | 5 88b | 5 63a | 4 31c | 3 63c |
| CD (5%) | 0 17 | 0 01 | 0 02 | 0 06 | 0 18 | 0 06 | 0 05 | 0 08 | 0 10 | 0 07 | 0 08 | 0 09 | 0 07 | 0 05 | 0 08 | 0 15 | 0 09 |

($V_1$): Rashmisali, ($V_2$): Bogajoha, ($V_3$): Basmuthi, ($V_4$): Lalkalamdani, ($V_5$): Choimora, ($V_6$): Mahsuri, ($V_7$): Moniram, ($V_8$): Kushal, ($V_9$): Gitesh, ($V_{10}$): Profulla

**Table 4.10. Yield and yield attributing parameters of rice varieties and seasonal integrated nitrous oxide emission flux ($E_{sif}$) in monsoon rice ecosystem. In each column, values with the same letters are not significantly different at $P<0.05$ level by Duncan's multiple range test.**

| Rice varieties/ parameters | Panicle square meter$^{-1}$ | Panicle length (cm) | Sterility (%) | Thousand grain weight (g) | Yield (q ha $^{-1}$) | $E_{sif}$ (mg $N_2O$-N $m^{-2}$) |
|---|---|---|---|---|---|---|
| **Rashmisali** | 246.16 f | 19.31 i | 11.38 e | 18.70 e | 34.60 d | 158.30 e |
| **Bogajoha** | 239.41 i | 20.33 c | 13.32 b | 18.30 h | 29.00 f | 174.80 b |
| **Basmuthi** | 235.36 j | 20.46 b | 13.59 a | 18.15 i | 28.80 f | 189.46 a |
| **Lalkalamdani** | 241.36 h | 19.50 g | 11.65 d | 18.65 f | 34.30 d | 168.93 c |
| **Choimora** | 243.44 g | 19.43 h | 12.42 c | 18.58 g | 32.50 e | 160.71d |
| **Mahsuri** | 273.09 a | 19.63 f | 9.87 h | 19.75 d | 36.80 bc | 140.54 g |
| **Moniram** | 248.37 e | 20.24 d | 10.42 f | 19.81 c | 36.30 c | 141.17 g |
| **Kushal** | 250.14 c | 20.32 c | 8.51 i | 20.23 b | 37.26 b | 129.39 h |
| **Gitesh** | 268.45 b | 19.88 e | 7.45 j | 20.76 a | 38.20 a | 121.63 i |
| **Profulla** | 249.36 d | 21.43 a | 10.19 g | 19.73 d | 36.50 c | 143.30 f |

## 4.3. Nitrous oxide emission estimation from rain-fed wheat ecosystem in relation to plant and soil parameters

### 4.3.1. Meteorological parameters

Figure 3.4. shows the meteorological parameters recorded during experimental period from December 2006 to April 2007. The minimum weekly average temperature of 11.35°C was recorded in the month of January, 2006. Maximum temperature of 34.57°C was recorded in April, 2007. Mean rainfall during crop growth period ranged from 0.47 mm to 15.94 mm. Maximum rainfall was recorded in the month of April.

### 4.3.2. Nitrous oxide flux (μg $N_2O$-N $m^{-2}$ $h^{-1}$)

Nitrous oxide emissions during the rain-fed wheat growing season varied from 12 to 291 μg $N_2O$-N $m^{-2}$ $h^{-1}$ (Fig. 4.19). Emission rate increased gradually from 18 DAS onwards and at 39 DAS, $N_2O$ flux of 273 μg $N_2O$-N $m^{-2}$ $h^{-1}$ was observed in variety HUW 234. $N_2O$ fluxes of 267, 233 and 222 μg $N_2O$-N $m^{-2}$ $h^{-1}$ were recorded in DBW 14, HUW 468 and in Sonalika, respectively. The flux values differed significantly among the verities ($P< 0.05$) at 39 DAS. Emission decreased considerably from 46 to 67 DAS. The mean $N_2O$ emission from 46 to 67 DAS were 86, 95,109 and 110 μg $N_2O$-N $m^{-2}$ $h^{-1}$ in Sonalika, HUW 234, DBW 14 and HUW 468, respectively. The rate of emission increased sharply after panicle initiation and at crop ripening stage and declined at harvest. During this period emission peaks were observed at 74, 81 and 94 DAS. The average emission rates from 74 to 102 DAS in Sonalika, HUW 468, HUW 234 and DBW 14 were 153, 165, 204 and 206 μg $N_2O$-N $m^{-2}$ $h^{-1}$, respectively. $N_2O$ emissions for the entire crop growth period ($E_{s:f}$) differed significantly among the varieties at $P< 0.05$ level by Duncan's multiple range test (Table 4.14). Higher seasonal emission of 384.67 mg $N_2O$-N $m^{-2}$ was recorded in wheat variety HUW 234 followed by DBW 14 (381.60 mg $N_2O$-N $m^{-2}$), HUW 468 (338.50 mg $N_2O$-N $m^{-2}$) and Sonalika (311.62 mg $N_2O$-N $m^{-2}$).

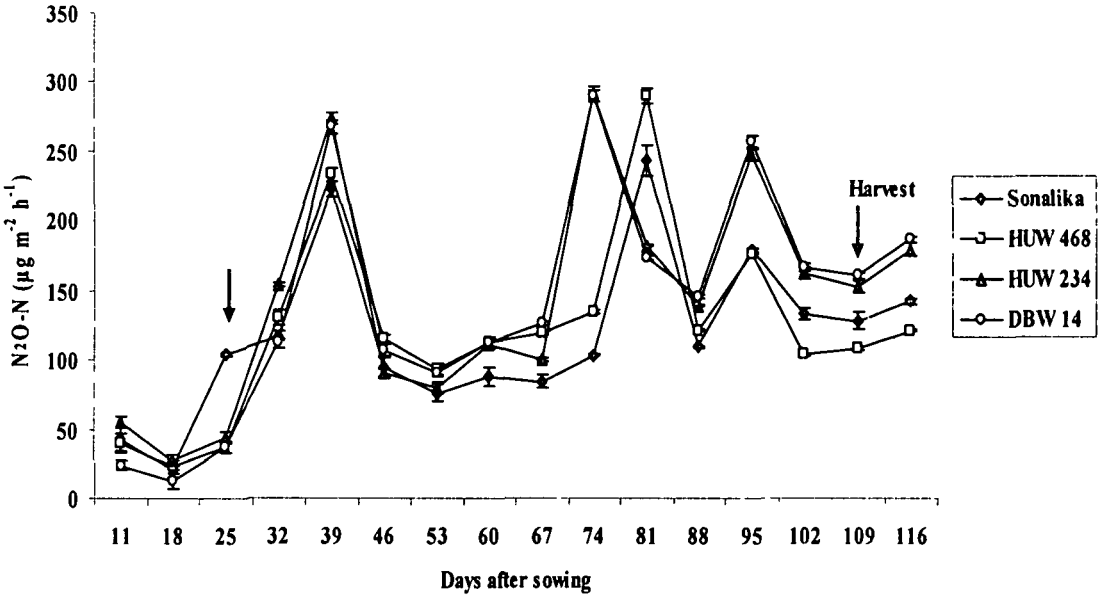


**Fig. 4.19. Nitrous oxide fluxes $N_2O$-N (µg $m^{-2}$ $h^{-1}$) from wheat varieties in rain-fed ecosystem. Vertical bars represent standard error of three replications. The arrows indicate the time of application of fertilizer and day of harvest.**

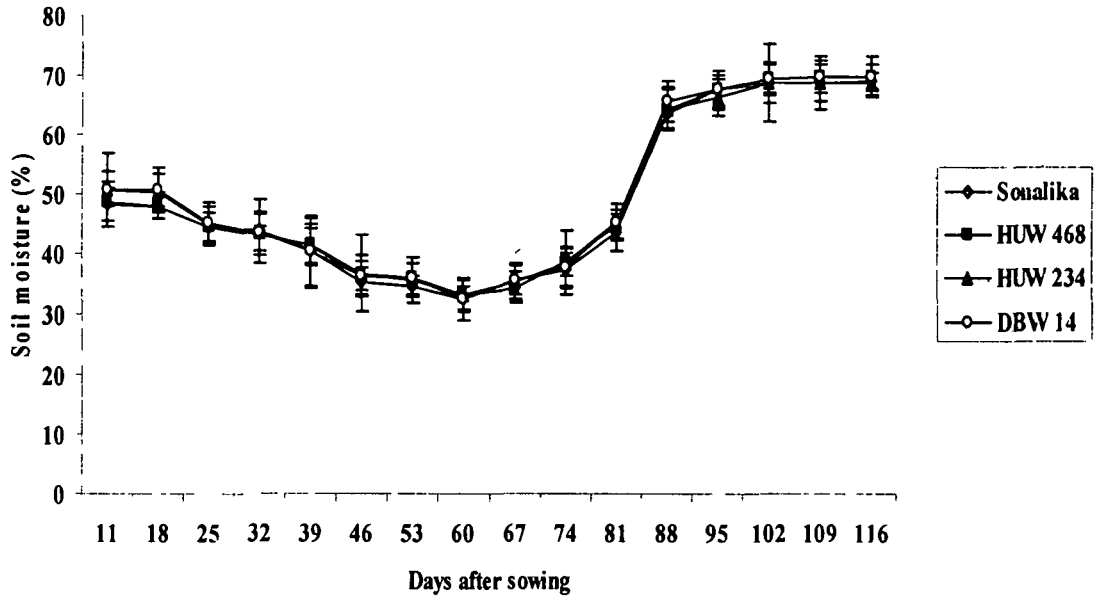


**Fig. 4.20. Soil moisture (%) of the experimental field during rain-fed wheat growing season. Vertical bars represent standard error of three replications.**

### 4.3.3. Soil moisture (%)

Soil moisture of the experimental field is presented in Figure 4.20. Mean soil moisture of the experimental field at 11 days after sowing (DAS) was 49.60%. Moisture content gradually decreased from 11 DAS onwards up to 60 DAS. With increasing rainfall after 67 DAT soil moisture increased till harvest.

### 4.3.4. Soil temperature ($^{o}$C)

Figure 4.21 represents the soil temperature of the experimental field. Soil temperature of the experimental field during the wheat growing season ranged from 17.3$^{o}$C to 29.0$^{o}$C. The relationship between soil temperature and $N_2O$ emission are significant in present study (Table 4.11).

### 4.3.5. Soil organic carbon (%)

Soil organic carbon of the experimental field varied from 0.93% to 1.23% (Figure 4.22). Soil organic carbon of experimental field showed increasing trend at flowering and ripening stage of the crop. The relationship between soil organic carbon and $N_2O$ emission are significant in present study (Table 4.11).

### 4.3.6. Soil nitrate nitrogen

Soil $NO_3^-$-N of the field increased gradually from 25 to 46 DAS and again from 74 to 95 DAS it showed an increasing trend (Figure 4.23). The soil $NO_3^-$-N content during crop growing season showed significant correlation with $N_2O$ emission (Table 4.11).

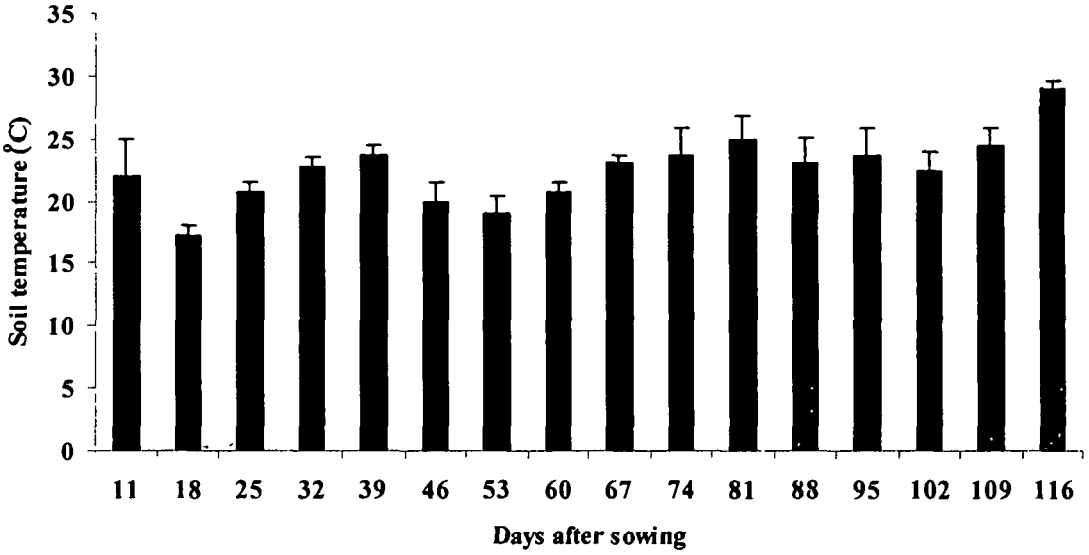


**Fig. 4.21. Soil temperature (°C) of the experimental field during rain-fed wheat growing season. Vertical bars represent standard error of three replications.**

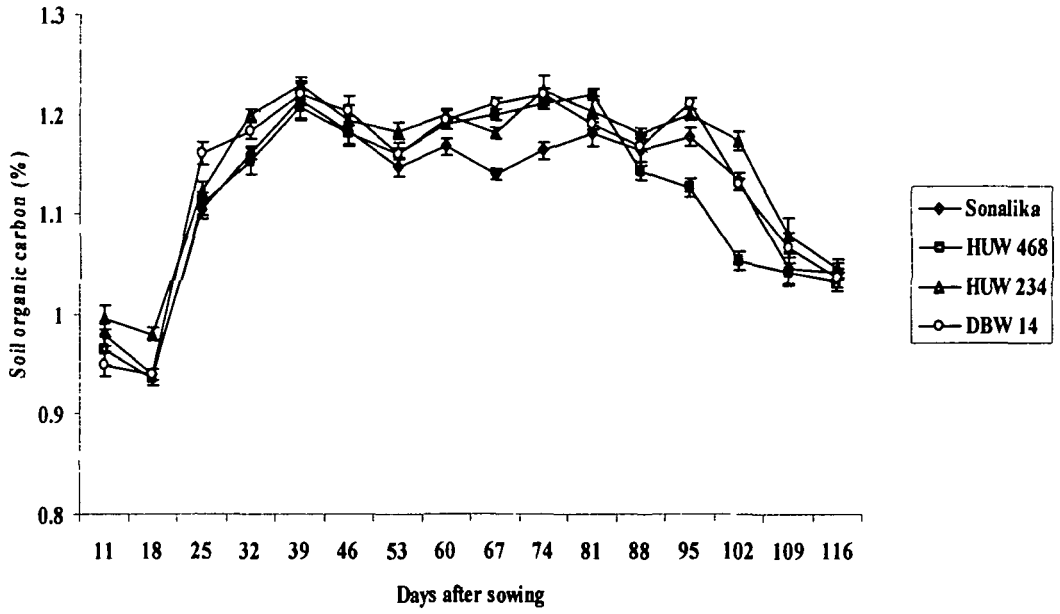


**Fig. 4.22. Soil organic carbon (%) of the experimental field during rain-fed wheat growing season. Vertical bars represent standard error of three replications.**

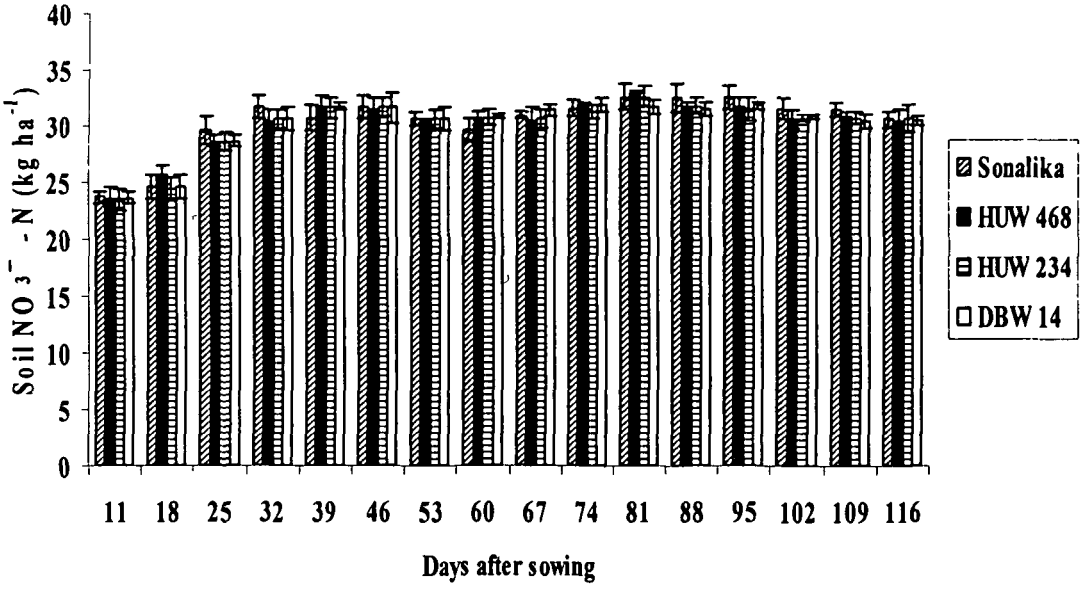


**Fig. 4.23. Soil $NO_3^-$ - N (kg ha $^{-1}$) of the experimental field during rain-fed wheat growing season. Vertical bars represent standard error of three replications.**

### 4.3.7. Leaf area ($cm^2$ $plant^{-1}$)

Table 4.13 represents the leaf area ($cm^2$ $plant^{-1}$) of wheat varieties. Leaf area at 11 DAS ranged between 7.57 $cm^2$ to 9.33 $cm^2$. Leaf area in all the varieties increased up to the grain-filling stage and declined thereafter. Higher leaf area values are recorded in varieties HUW 234 and DBW 14 at various growth stages. Varietal difference of leaf area was recorded.

### 4.3.8. Shoot dry weight (g $plant^{-1}$)

Table 4.13 represents the shoot dry weight (g $plant^{-1}$) of wheat varieties. At 11 DAS shoot dry weight varied from 0.12g to 0.17g. Shoot dry weight continuously increased from 11 DAS onwards and reached a maximum value at 88 DAS. HUW 234 and DBW 14 recorded higher shoot dry weight at various growth stages. $N_2O$ emissions showed significant correlations with shoot dry weight (Table 4.11).

### 4.3.9. Root dry weight (g $plant^{-1}$)

Root dry weight (g $plant^{-1}$) of wheat varieties are shown in Table 4.13. Root dry weights increased gradually from 11 DAS and declined at crop maturity stage (95 DAS onwards). The correlations between and $N_2O$ emission and root dry weights are significant in present study (Table 4.11).

### 4.3.10. Yield and yield attributing parameters

Yield and yield attributing characteristics of wheat varieties are presented in Table 4.14. Maximum yield was recorded in wheat varieties DBW 14 followed by Sonalika, HUW 234 and HUW 468. Thousand grain weights of 55.34g, 54.21g,

48.76g and 41.26g were recorded in DBW 14, Sonalika, HUW 468 and HUW 234. Grain sterility in terms of unfilled grains was found to be higher in HUW 468. Panicle length of 14.63cm and 13.80cm are recorded in variety HUW 468 and Sonalika, respectively. DBW 14 followed by HUW 234 recorded maximum panicle number per unit area (square meter $^{-1}$).

The total variance explained by factors is indicated in Table 4.12. The loadings indicate the contribution of each variable to the factors. The factor loadings greater than 0.70 are considered important and are highlighted in bold. Three factors with eigenvalues > 1 were extracted. Factor 1, 2 and 3 accounts for about 59.97%, 19.84% and 13.13%, respectively of total variance explained. The variables; leaf area, root dry weight and shoot dry weight have shown high loadings in factor 1 and are positively associated. In factor 2 the parameters with greatest positive weight are $N_2O$ flux, soil temperature, soil organic carbon and soil $NO_3^-$-N. A significant positive interrelationship between these parameters exists. These finding suggest that in rain-fed wheat, the main parameters associated with $N_2O$ emission are soil temperature, SOC and soil $NO_3^-$-N. Although soil moisture is strongly loaded in factor 3 the associations between soil moisture with other variables in factor 3 are not significant. The results are accepted for publication in *J. Pedosphere*, 2011, ISSN 1002-0160/CN 32-1315/P, in press, (Elsevier).

**Table 4.11. Correlation of plant and soil parameters with nitrous oxide emission during rain-fed wheat growing season.**

| Parameters | Correlation with nitrous oxide emission |
|---|---|
| Organic carbon (%) | 0.725** |
| Soil $NO_3^-$ - N (kg $ha^{-1}$) | 0.742** |
| Soil temperature ($^oC$) | 0.801** |
| Soil moisture (%) | 0.126 |
| Leaf area ($cm^2$ $hill^{-1}$) | 0.420 |
| Root dry weight (g $hill^{-1}$) | 0.507* |
| Shoot dry weight (g $hill^{-1}$) | 0.530* |

*Correlation is significant at the 0.05 level of significance

**Correlation is significant at the 0.01 level of significance

$^{NS}$Non- significant

**Table 4.12. Principal factor matrix after varimax rotation (rain-fed wheat and summer rice ecosystem).**

| Variables | Factor | | | Proportion of each variable's variance explained by the underlying factors |
|---|---|---|---|---|
| | 1 | 2 | 3 | |
| **Wheat** | | | | |
| $N_2O$ flux | 0.229 | **0.919**[a)] | | 0.904 |
| Soil $NO_3^-$-N | 0.569 | **0.717** | -0.198 | 0.877 |
| Soil organic carbon | 0.441 | **0.759** | -0.410 | 0.939 |
| Soil moisture | 0.102 | | **0.957** | 0.928 |
| Soil temperature | 0.165 | **0.856** | 0.281 | 0.839 |
| Leaf area | **0.899** | 0.239 | -0.320 | 0.967 |
| Shoot dry weight | **0.853** | 0.327 | 0.394 | 0.990 |
| Root dry weight | **0.892** | 0.294 | 0.331 | 0.992 |
| Eigenvalues | 4.798 | 1.588 | 1.051 | |
| % of Variance | 59.973 | 19.847 | 13.138 | |
| Cumulative % | 59.973 | 79.820 | 92.958 | |
| **Rice** | | | | |
| $N_2O$ flux | **0.834** | 0.213 | | 0.741 |
| Soil $NO_3^-$-N | **0.943** | 0.187 | | 0.924 |
| Soil organic carbon | **0.830** | 0.519 | | 0.959 |
| Field water | | **-0.972** | | 0.948 |
| Soil temperature | 0.591 | 0.691 | | 0.827 |
| Leaf area | **0.915** | 0.335 | | 0.950 |
| Shoot dry weight | 0.509 | **0.831** | | 0.950 |
| Root dry weight | 0.653 | **0.737** | | 0.970 |
| Eigenvalues | 6.148 | 1.120 | | |
| % of Variance | 76.846 | 13.994 | | |
| Cumulative % | 76.846 | 90.841 | | |

[a)]Numbers in bold are those with factor loadings greater than 0.70.

**Table 4.13. Variations in leaf area, shoot dry weight, root dry weight within wheat varieties compared by one-way ANOVA in rain-fed wheat ecosystem. In each column, values with the similar letters are not significantly different at $P< 0.05$ level by Duncan's multiple range test.**

| | Days after sowing | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 11 | 18 | 25 | 32 | 39 | 46 | 53 | 60 | 67 | 74 | 81 | 88 | 95 | 102 |
| **Leaf area ($cm^2$ $hill^{-1}$)** | | | | | | | | | | | | | | |
| **Sonalika** | 7.73a | 18.16b | 69.14c | 162.23b | 208.53c | 406.23c | 685.08c | 752.07c | 778.22b | 747.45c | 640.00c | 588.00a | 556.00a | 465.19a |
| **HUW 468** | 9.33a | 21.30b | 73.27b | 145.31c | 197.32d | 347.00d | 656.00d | 709.00d | 767.27b | 755.17bc | 612.16d | 545.22c | 508.50bc | 420.19c |
| **HUW 234** | 8.50a | 29.53a | 96.66a | 209.32a | 280.45a | 544.23a | 741.26a | 786.19a | 799.25a | 784.14a | 691.30a | 560.23b | 513.85b | 379.25d |
| **DBW 14** | 7.57a | 19.14b | 74.22b | 120.26d | 256.17b | 515.27b | 712.14b | 772.45b | 793.15a | 762.12b | 670.13b | 529.12d | 500.18c | 447.24b |
| **CD (5%)** | 2.05 | 5.96 | 1.33 | 12.77 | 4.59 | 2.81 | 5.37 | 1.63 | 11.41 | 10.33 | 7.84 | 12.80 | 11.05 | 9.29 |
| **Shoot dry weight (g $hill^{-1}$)** | | | | | | | | | | | | | | |
| **Sonalika** | 0.12b | 0.18bc | 0.23b | 0.71a | 0.96b | 1.89c | 2.29c | 5.50c | 6.79a | 7.43ab | 8.41b | 9.46bc | 9.36b | 9.00b |
| **HUW 468** | 0.16ab | 0.14c | 0.27a | 0.54b | 0.77d | 1.74d | 2.29c | 4.98d | 6.12b | 7.06b | 7.86c | 9.17c | 9.06c | 8.10c |
| **HUW 234** | 0.14ab | 0.20ab | 0.27a | 0.65a | 1.25a | 2.53b | 3.16b | 5.71b | 6.83a | 7.91a | 9.49a | 10.31a | 10.23a | 9.80a |
| **DBW 14** | 0.17a | 0.25a | 0.27a | 0.30c | 0.90c | 3.01a | 4.50a | 5.92a | 6.20b | 6.50c | 8.50b | 9.70b | 9.00c | 8.80b |
| **CD (5%)** | 0.04 | 0.05 | 0.03 | 0.08 | 0.04 | 0.08 | 0.07 | 0.17 | 0.29 | 0.54 | 0.48 | 0.31 | 0.29 | 0.53 |
| **Root dry weight (g $hill^{-1}$)** | | | | | | | | | | | | | | |
| **Sonalika** | 0.05b | 0.05b | 0.07c | 0.11a | 0.33a | 1.21b | 1.98c | 2.39a | 3.10ab | 3.48a | 4.27ab | 4.47b | 4.36a | 4.19ab |
| **HUW 468** | 0.04b | 0.04b | 0.06d | 0.08a | 0.17a | 1.52b | 2.09b | 2.30a | 2.82b | 3.43a | 4.08b | 4.40b | 4.51a | 4.40ab |
| **HUW 234** | 0.05b | 0.08a | 0.09a | 0.14a | 0.22a | 2.00a | 2.58a | 2.68a | 3.63a | 3.96a | 4.87a | 4.98a | 4.33a | 4.05b |
| **DBW 14** | 0.07a | 0.07a | 0.08b | 0.13a | 0.40a | 1.72b | 2.08b | 2.50a | 3.36ab | 3.73a | 4.35ab | 4.65ab | 4.66a | 4.54a |
| **CD (5%)** | 0.01 | 0.02 | 0.01 | 0.07 | 0.26 | 0.53 | 1.10 | 0.52 | 0.71 | 0.94 | 0.65 | 0.45 | 0.35 | 0.38 |

**Table 4.14. Comparisons of yield and yield attributing parameters of wheat varieties and seasonal integrated nitrous oxide emission flux ($E_{sif}$) in rain-fed wheat ecosystem. In each column, values with the same letters are not significantly different at $P<0.05$ level by Duncan's multiple range test.**

| Wheat varieties/ parameters | Panicle square meter$^{-1}$ | Panicle length (cm) | Sterility (%) | Thousand grain weight (g) | Yield (q ha$^{-1}$) | $E_{sif}$ (mg $N_2O$-N $m^{-2}$) |
|---|---|---|---|---|---|---|
| **Sonalika** | 228.60b | 13.80ab | 11.24c | 54.21a | 30.44b | 311.62d |
| **HUW 468** | 221.80c | 14.63a | 12.32a | 48.76b | 26.68d | 338.50c |
| **HUW 234** | 234.40a | 12.90b | 11.93b | 41.26c | 28.41c | 384.67a |
| **DBW 14** | 239.20a | 12.55b | 10.21d | 55.34a | 31.06a | 381.60b |

## 4.4. Nitrous oxide emission estimation from summer rice (*Boro*) ecosystem in relation to plant and soil parameters

### 4.4.1. Meteorological parameters

Meteorological parameters recorded during experimental period are presented in Figure 3.4. Average minimum and maximum temperature during crop growing season ranged from 9.21°C to 35.97°C. Maximum average rainfall of 16.80 mm was recorded in the month of February 2007.

### 4.4.2. Nitrous oxide flux (μg $N_2O$-N $m^{-2}$ $h^{-1}$)

Nitrous oxide emission in rice ranged from 11 to 154 μg $N_2O$-N $m^{-2}$ $h^{-1}$ (Fig. 4.24). All the three rice varieties showed similar patterns of $N_2O$ emission. The average $N_2O$ flux at transplanting (0 DAT) was 19 μg $N_2O$-N $m^{-2}$ $h^{-1}$. From 7 DAT onwards rate of emission gradually increased in the varieties and at 35 DAT, $N_2O$ fluxes of 123 and 110 μg $N_2O$-N $m^{-2}$ $h^{-1}$ were observed in the varieties Joymoti and Kanaklata, respectively. In Bishnuprasad an emission peak of 121 μg $N_2O$-N $m^{-2}$ $h^{-1}$ was recorded at 42 DAT. The second emission peaks were recorded at 63 DAT in Joymoti and at 70 DAT in Kanaklata and Bishnuprasad. Third emission peaks were recorded at 112 DAT in all the rice varieties. Seasonal integrated nitrous oxide emission ($E_{sif}$) recorded from rice varieties showed significant differences among the varieties and Joymoti with higher emission (Table 4.17).

### 4.4.3. Water level (cm)

Water level of the experimental field ranged from 1.33cm to 4.10cm during crop growing season (Fig. 4.25). Maximum standing water was recorded at 28 DAT and 49 DAT. From 91 DAT onwards standing water level of field ceased completely.

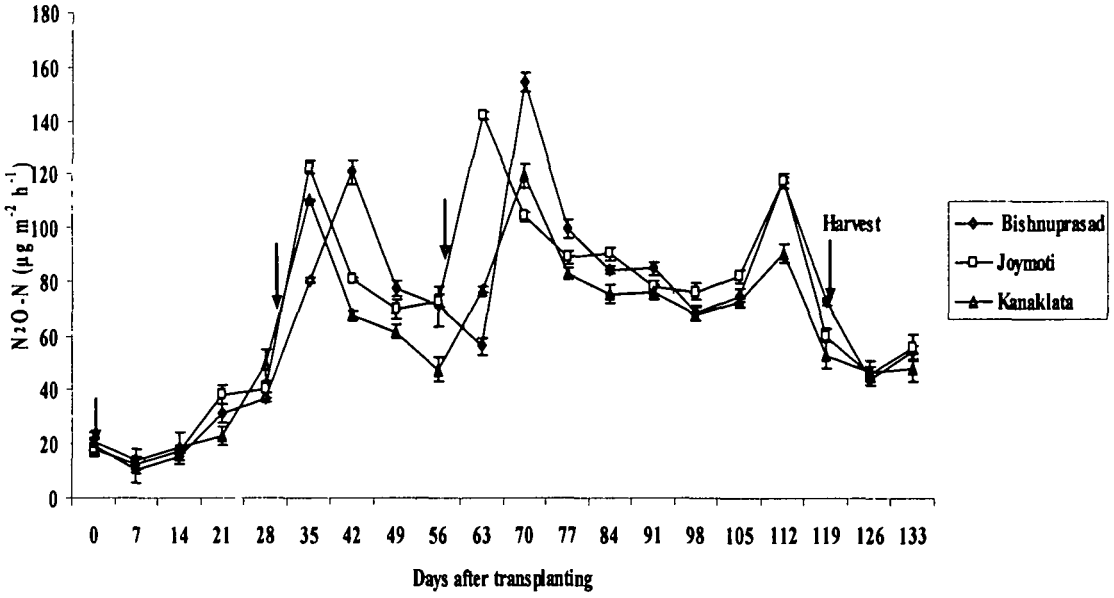


**Fig. 4.24. Nitrous oxide fluxes $N_2O$-N ($\mu g\ m^{-2}\ h^{-1}$) from rice varieties in summer rice ecosystem. Vertical bars represent standard error of three replications. The arrows indicate the time of application of fertilizer and day of harvest.**

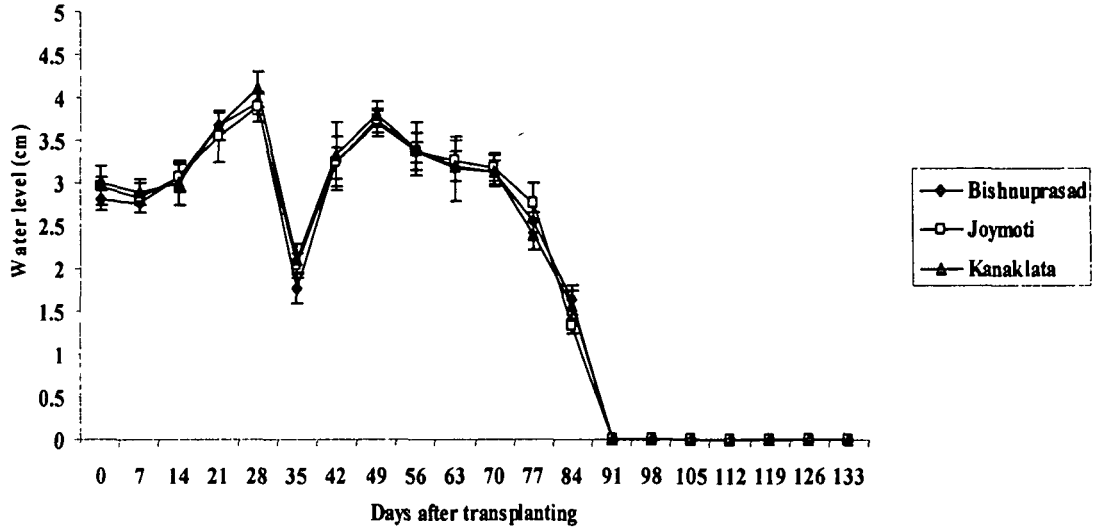


**Fig. 4.25. Water level of the experimental field during summer rice growing season. Vertical bars represent standard error of three replications.**

### 4.4.4. Soil temperature (°C)

Soil temperature during crop growing season ranged from 16.0°C-31.0°C (Fig. 4.26). With increasing air temperature soil temperature gradually increased from 7 DAT onwards and maximum soil temperature was recorded at 112 DAT. $N_2O$ emissions showed significant positive correlation with soil temperature (Table 4.15).

### 4.4.5. Soil organic carbon (%)

Soil organic carbon during the rice growing season varied from 0.95% to 1.40% (Fig. 4.27). Soil organic carbon of the experimental field was initially low and increased during flowering and ripening stage. The observed significant relationship between soil organic carbon and $N_2O$ emission are presented in Table 4.15.

### 4.4.6. Soil nitrate nitrogen

Soil $NO_3^-$-N gradually increased from transplanting onwards (Fig. 4.28), higher soil $NO_3^-$ was observed at 63 DAT. The soil $NO_3^-$-N content showed significant positive correlation with $N_2O$ emission (Table 4.15).

### 4.4.7. Leaf area ($cm^2$ $hill^{-1}$)

Leaf area of rice varieties at 7 DAT ranged from 48.88 $cm^2$ to 50.27 $cm^2$. From 7 DAT onwards the leaf area increased up to panicle emergence stage (Table 4.16). At different growth stages leaf area varied within the varieties. The relationship between $N_2O$ emission and leaf area in the present study is found to be significant (Table 4.15).

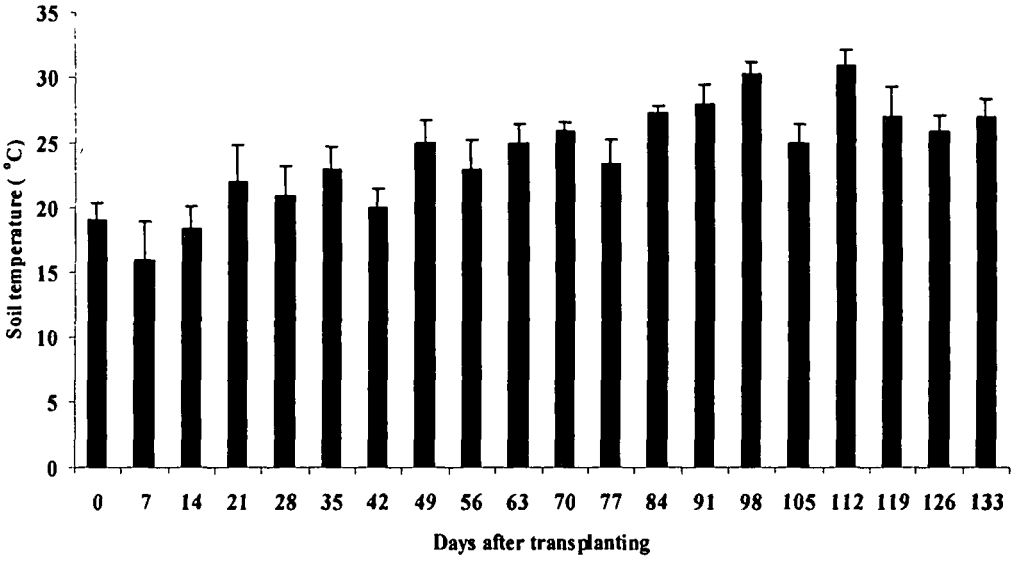


**Fig. 4.26. Soil temperature (°C) of the experimental field during summer rice growing season. Vertical bars represent standard error of three replications.**

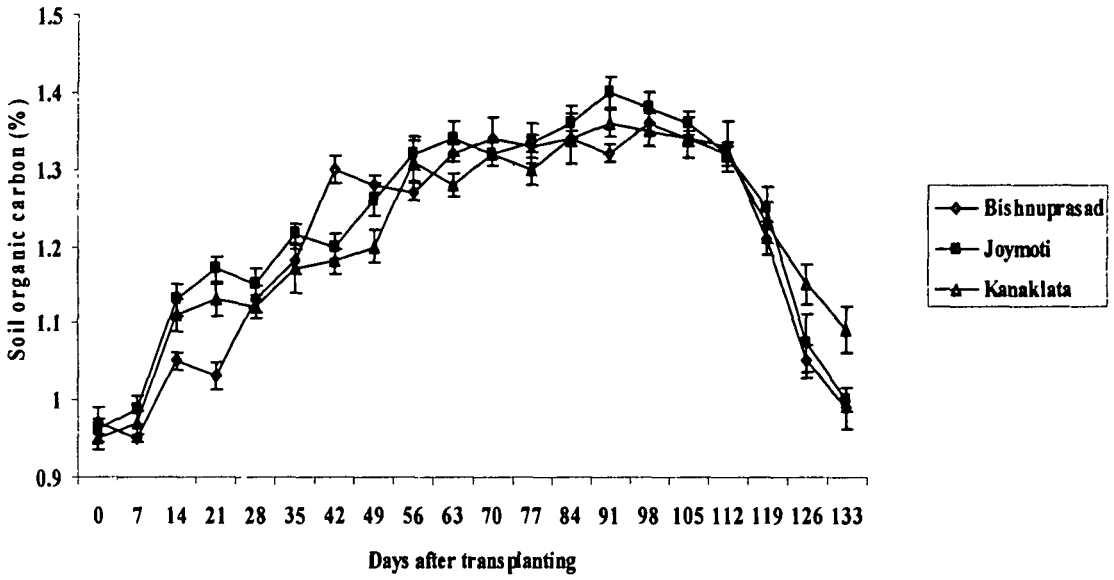


**Fig. 4.27. Soil organic carbon (%) of the experimental field during summer rice growing season. Vertical bars represent standard error of three replications.**

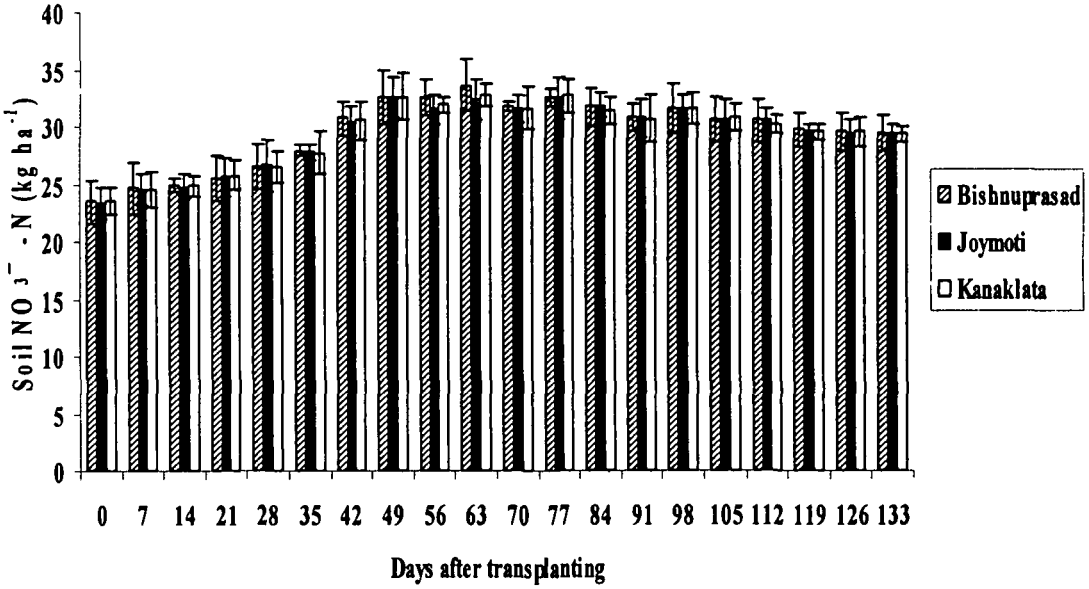


**Fig. 4.28. Soil $NO_3^-$ - N (kg ha $^{-1}$) of the experimental field during summer rice growing season. Vertical bars represent standard error of three replications.**

### 4.4.8. Shoot dry weight (g hill$^{-1}$)

Shoot dry weights increased gradually from 7 DAT onwards and showed maximum at 105 DAT (Table 4.16). Shoot dry weights of rice variety Joymoti was higher compared to Bishnuprashad and Kanaklata at different growth stages.

### 4.4.9. Root dry weight (g hill$^{-1}$)

Root dry weights increased gradually from 7 DAT onwards up to crop maturity and declined at harvest (Table 4.16). Root dry weight of rice variety Joymoti was higher compared to Bishnuprashad and Kanaklata. Both shoot and root dry weights have recorded a significant relationship with $N_2O$ emission (Table 4.15).

### 4.4.10. Yield and yield attributing parameters

Table 4.17 presents the data recorded on yield and yield attributing characteristics of rice varieties. Maximum yield of 33.20 q ha $^{-1}$ was recorded in Kanaklata followed by Bishnuprasad and Joymoti. Thousand grain weights of 20.36g, 20.16g and 20.10g are recorded in Bishnuprasad, Kanaklata and Joymoti. Grain sterility was higher (unfilled grains 11.53%) in variety Joymoti. Variety Kanaklata recorded maximum panicle length and number of panicle per square meter. Variation in yield and yield attributing characteristics differed significantly within varieties.

Results of the factor analysis are presented in Table 4.12. Two factors with eigenvalues > 1 were extracted, accounting for 90% of the total variance. Factor 1 account for 76.84% of total variance and had very high loadings for soil $NO_3^-$-N, leaf area, $N_2O$ flux and soil organic carbon. All these variables were positively associated. Factor 1 indicates that increases in $N_2O$ emissions were strongly associated with increased in soil $NO_3^-$-N, leaf area and soil organic carbon in rice. Root and shoot dry weights were also positively related to $N_2O$ emissions but had factor

loadings < 0.70 and hence were considered to be less important. Factor 2 accounted for 14% of total variance. Although factor 2 was highly loaded with shoot dry weight, root dry weight and field water level the association between these variables with $N_2O$ emission was not significant. The main parameters influencing $N_2O$ emission in summer (*Boro*) rice ecosystem were soil $NO_3^-$-N, leaf area and soil organic carbon. The results are accepted for publication in *J. Pedosphere*, 2011, (Elsevier). ISSN 1002-0160/CN 32-1315/P, in press.

**Table 4.15. Correlation of plant and soil parameters with nitrous oxide emission during summer rice growing season.**

| Parameters | Correlation with nitrous oxide emission |
|---|---|
| Organic carbon (%) | 0.756** |
| Soil $NO_3^-$ - N (kg $ha^{-1}$) | 0.739** |
| Soil temperature ($^oC$) | 0.652** |
| Water level (cm) | $-0.321^{NS}$ |
| Leaf area ($cm^2$ $hill^{-1}$) | 0.771** |
| Root dry weight (gm $hill^{-1}$) | 0.662** |
| Shoot dry weight (g $hill^{-1}$) | 0.559* |

*Correlation is significant at the 0.05 level of significance

**Correlation is significant at the 0.01 level of significance

$^{NS}$Non significant

**Table 4.16. Variations in leaf area, shoot dry weight and root dry weight within rice varieties compared by one-way ANOVA in summer rice ecosystem. In each column, values with the similar letters are not significantly different at $P< 0.05$ level by Duncan's multiple range test.**

| | Days after transplanting | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 7 | 14 | 21 | 28 | 35 | 42 | 49 | 56 | 63 | 70 | 77 | 84 | 91 | 98 | 105 | 112 |
| **Leaf area ($cm^2$ $hill^{-1}$)** | | | | | | | | | | | | | | | | |
| $V_1$ | 48.88a | 106.92a | 205.97a | 312.33a | 388.89a | 455.62a | 535.97a | 607.15b | 693.59b | 794.05b | 780.28b | 762.63b | 683.35c | 646.91c | 554.82c | 490.86c |
| $V_2$ | 49.62a | 108.05a | 192.65b | 318.87a | 386.98a | 455.27a | 535.03a | 645.51a | 752.67a | 866.63a | 848.54a | 831.28a | 716.90b | 695.90b | 581.32b | 512.85b |
| $V_3$ | 50.27a | 109.00a | 202.28ab | 319.25a | 370.24b | 440.94b | 527.56b | 585.21c | 624.23c | 759.85c | 779.31b | 771.64b | 728.29a | 710.11a | 663.99a | 546.24a |
| CD (5%) | 2.75 | 10.04 | 12.23 | 7.67 | 9.54 | 5.51 | 4.10 | 10.80 | 8.08 | 4.45 | 11.23 | 11.91 | 8.22 | 7.14 | 23.11 | 11.41 |
| **Shoot dry weight (g $hill^{-1}$)** | | | | | | | | | | | | | | | | |
| $V_1$ | 0.29a | 0.42c | 0.86a | 1.48a | 1.78b | 3.65a | 4.80b | 7.62b | 11.53b | 19.74c | 24.51b | 27.32b | 29.43b | 30.18c | 31.21c | 31.09c |
| $V_2$ | 0.32a | 0.69a | 0.93a | 1.52a | 2.86a | 3.80a | 5.68a | 17.00a | 25.00a | 29.50a | 33.30a | 35.10a | 36.00a | 36.18a | 36.41a | 35.93a |
| $V_3$ | 0.26a | 0.56b | 0.83a | 1.35a | 1.99b | 3.27a | 4.75b | 7.21b | 10.29c | 20.84b | 23.46b | 26.31b | 30.28b | 32.15b | 33.08b | 32.87b |
| CD (5%) | 0.11 | 0.09 | 0.15 | 0.23 | 0.81 | 0.79 | 0.18 | 1.01 | 0.89 | 0.62 | 2.17 | 1.76 | 1.34 | 1.13 | 1.06 | 0.66 |
| **Root dry weight (g $hill^{-1}$)** | | | | | | | | | | | | | | | | |
| $V_1$ | 0.09a | 0.14b | 0.21b | 0.43b | 0.90b | 1.50a | 1.75a | 2.13b | 2.69ab | 3.66a | 3.94a | 4.15a | 4.36a | 4.44a | 4.27a | 3.90b |
| $V_2$ | 0.06a | 0.10c | 0.28a | 0.56a | 1.15a | 1.25ab | 1.60ab | 2.48a | 3.51a | 3.81a | 4.07a | 4.36a | 4.69a | 4.72a | 4.63a | 4.55a |
| $V_3$ | 0.10a | 0.18a | 0.30a | 0.45b | 0.88b | 1.00b | 1.20b | 1.48c | 2.00b | 3.00a | 3.15b | 3.32b | 3.45b | 3.55b | 3.60b | 3.45c |
| CD (5%) | 0.06 | 0.03 | 0.06 | 0.10 | 0.16 | 0.41 | 0.46 | 0.27 | 0.98 | 1.06 | 0.58 | 0.41 | 0.81 | 0.40 | 0.45 | 0.16 |

($V_1$: Bishnuprasad, $V_2$: Joymoti, $V_3$: Kanaklata)

**Table 4.17. Yield and yield attributing parameters of rice varieties and seasonal integrated nitrous oxide emission flux ($E_{sif}$) in summer rice ecosystem. In each column, values with the same letters are not significantly different at $P<0.05$ level by Duncan's multiple range test.**

| Rice varieties/ parameters | Panicle square meter$^{-1}$ | Panicle length (cm) | Sterility (%) | Thousand grain weight (g) | Yield (q ha$^{-1}$) | $E_{sif}$ (mg $N_2O$-N $m^{-2}$) |
|---|---|---|---|---|---|---|
| Bishnuprasad | 248.20b | 20.35b | 11.05b | 20.36 a | 32.61b | 206.29b |
| Joymoti | 246.83c | 19.63c | 11.53a | 20.10 b | 31.98c | 216.37a |
| Kanaklata | 250.79a | 20.86a | 10.32c | 20.16 b | 33.20a | 190.11c |

## 4.5. Nitrous oxide emission estimation from irrigated wheat ecosystem in relation to plant and soil parameters

### 4.5.1. Meteorological parameters

Meteorological parameters recorded during experimental period are presented in Figure 3.5. Average maximum air temperature of 32.6°C was recorded during crop growing season. Maximum average rainfall of 9.43 mm was recorded in the month of April.

### 4.5.2. Nitrous oxide flux (μg $N_2O$-N $m^{-2}$ $h^{-1}$)

The $N_2O$ emission fluxes from the wheat varieties varied from 40.67 μg $N_2O$-N $m^{-2}$ $h^{-1}$ to 295.67 μg $N_2O$-N $m^{-2}$ $h^{-1}$ (Fig. 4.29). Significant variations in seasonal integrated $N_2O$ flux ($E_{sif}$) values, within the wheat varieties were recorded (Table 4.20). The highest seasonal integrated nitrous oxide flux ($E_{sif}$) was recorded in the wheat variety HUW 234 (380.91 mg $N_2O$-N $m^{-2}$) followed by DBW 14 (375.48 mg $N_2O$-N $m^{-2}$), HUW 468 (339.02 mg $N_2O$-N $m^{-2}$) and Sonalika (325.24 mg $N_2O$-N $m^{-2}$). Wheat varieties showed first emission peak at 26 days after sowing and the second emission peak was recorded at tillering stage (47 DAS) in all the varieties. The third emission peak was recorded at 82 DAS in HUW 234 and HUW 468, whereas in DBW 14 and Sonalika it was recorded at 89 DAS. Thereafter, $N_2O$ emission showed a decreasing trend.

### 4.5.3. Soil moisture (%)

The recorded average soil moisture of the experimental field was 45.16% at 12 DAS (Fig. 4.30). Increasing trend in soil moisture was observed from 75 DAS onwards and reached a maximum of 69% at harvest.

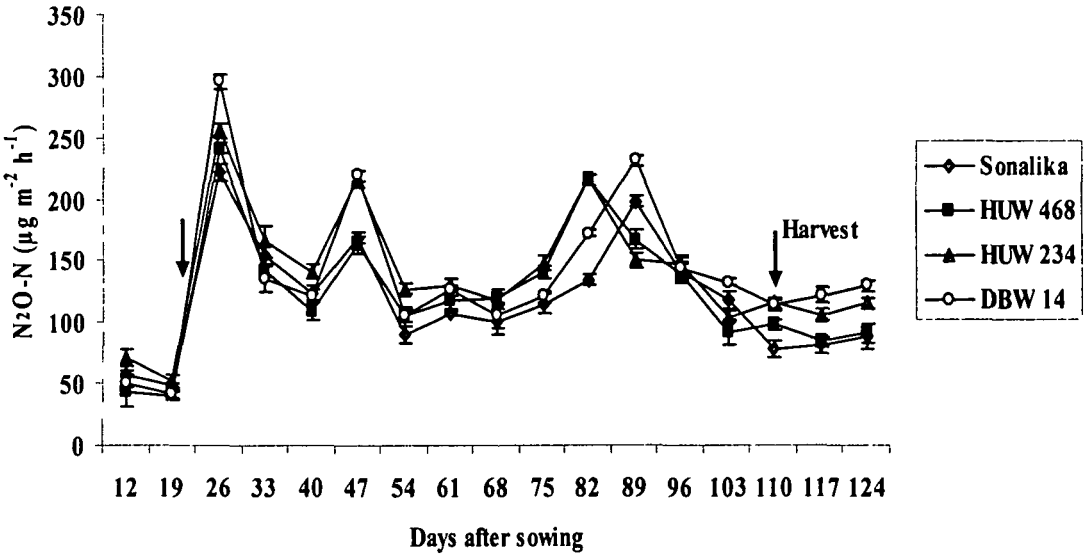


**Fig. 4.29. Nitrous oxide fluxes $N_2O$-N (µg $m^{-2}$ $h^{-1}$) from wheat varieties in irrigated ecosystem. Vertical bars represent standard error of three replications. The arrows indicate the time of application of fertilizer and day of harvest.**

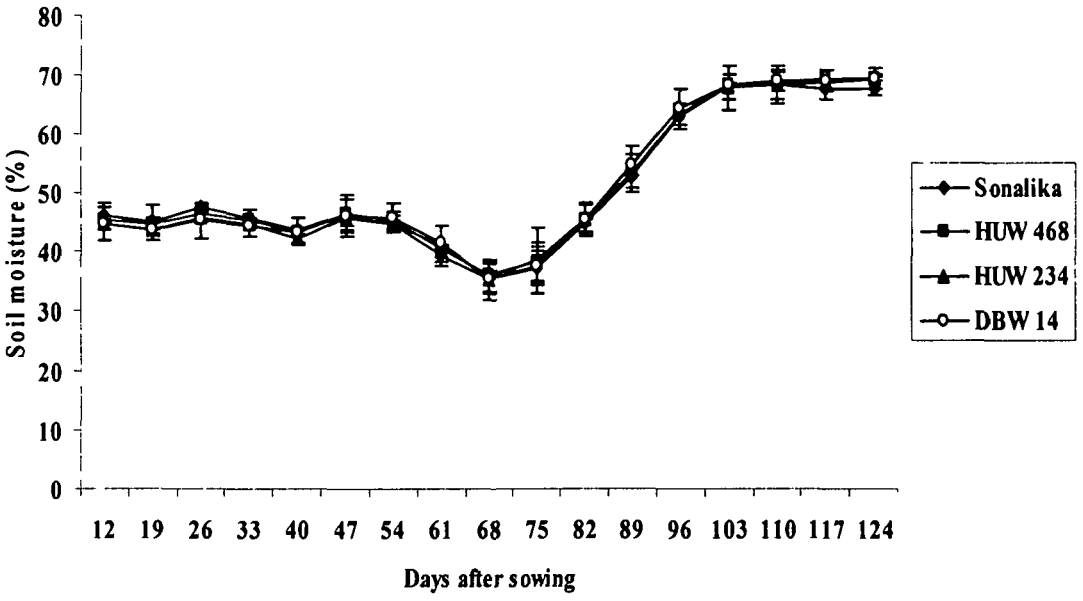


**Fig. 4.30. Soil moisture (%) of the experimental field during irrigated wheat growing season. Vertical bars represent standard error of three replications.**

### 4.5.4. Soil temperature (°C)

Soil temperature ranged from 19.0°C to 25.0°C during crop growing season (Fig. 4.31). $N_2O$ emission showed significant positive correlations with soil temperature (Table 4.18).

### 4.5.5. Soil organic carbon (%)

Soil organic carbon of the experimental field varied from 0.96% to 1.22% (Fig. 4.32). The relationship between soil organic carbon and $N_2O$ emission are significant in present study (Table 4.18).

### 4.5.6. Soil nitrate nitrogen

Figure 4.33 represents the soil $NO_3^-$-N of the experimental field. Soil $NO_3^-$-N of experimental field was initially low but it increased at heading stage (75 DAS onwards) and declined at harvest. Soil $NO_3^-$-N had a significant correlation with $N_2O$ emission (Table 4.18).

### 4.5.7. Soil pH

Soil pH of the experimental field ranged from 5.4 to 6.2 (Fig. 4.34). However, the soil pH did not have a significant relationship with $N_2O$ emission (Table 4.18).

### 4.5.7. Plant height (cm)

Plant height at 12 DAS varied from 5.83 cm – 7.36 cm (Fig. 4.35). Increased in plant height was recorded from 61 DAS to crop ripening stage. There was no significant relationship of $N_2O$ emission and plant height.

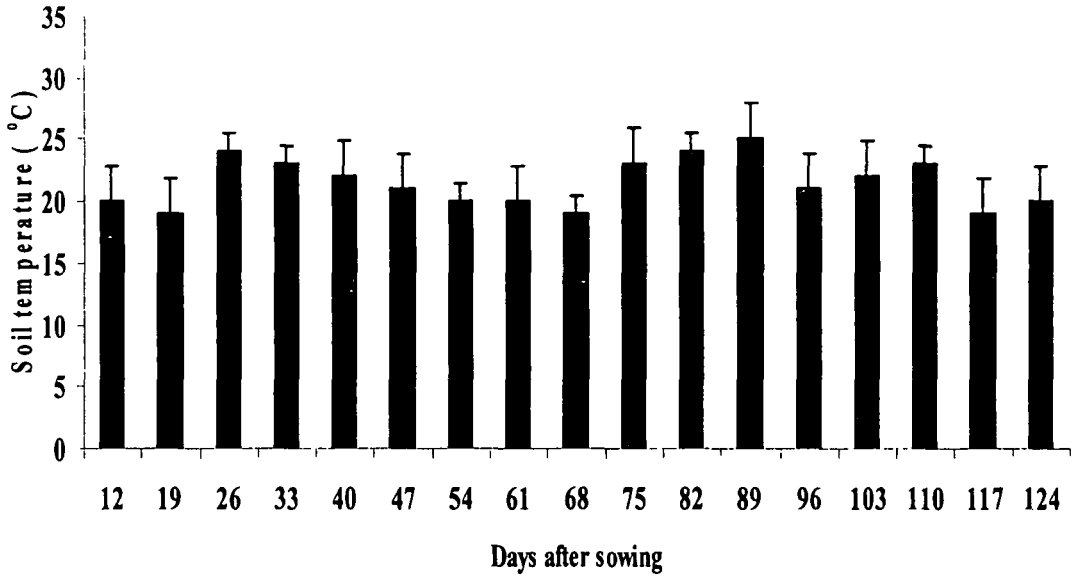


**Fig. 4.31. Soil temperature (°C) of the experimental field during irrigated wheat growing season. Vertical bars represent standard error of three replications.**

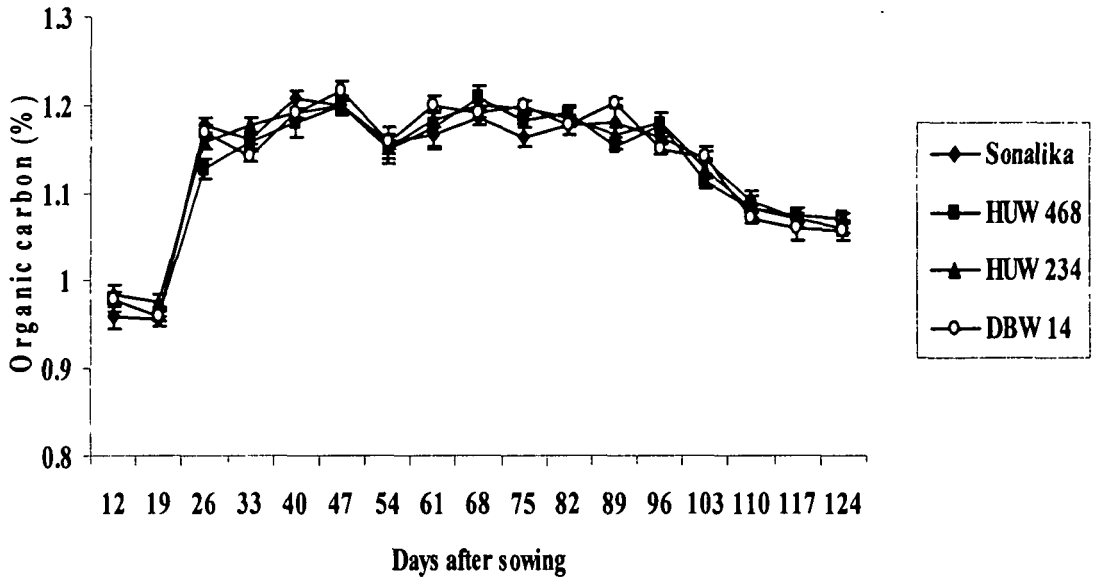


**Fig. 4.32. Soil organic carbon (%) of the experimental field during irrigated wheat growing season. Vertical bars represent standard error of three replications.**

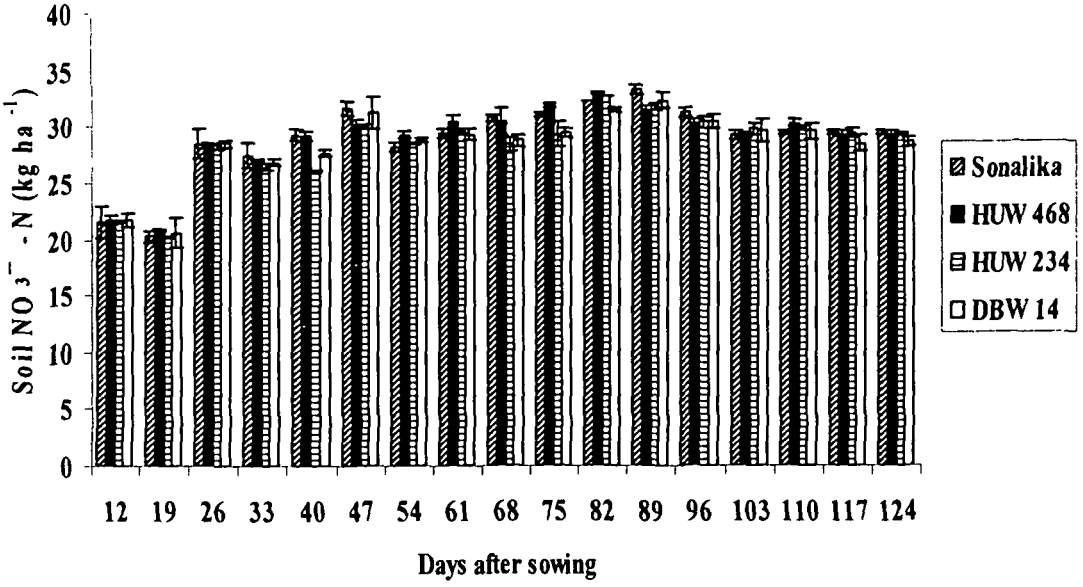


**Fig. 4.33. Soil $NO_3^-$ - N (kg ha $^{-1}$) of the experimental field during irrigated wheat growing season. Vertical bars represent standard error of three replications.**

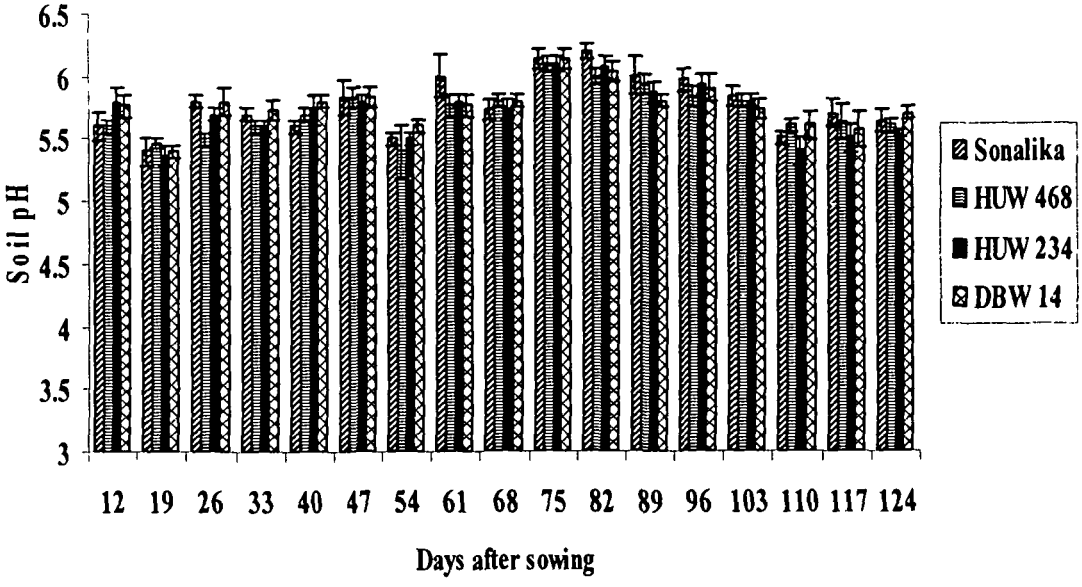


**Fig. 4.34. Soil pH of the experimental field during irrigated wheat growing season. Vertical bars represent standard error of three replications.**

### 4.5.8. Tiller number (plant$^{-1}$)

Number of tillers per plant increased till 75 DAS and declined thereafter in the varieties (Fig. 4.36). The relationship between $N_2O$ emission and tiller number in the present study is not significant (Table 4.18).

### 4.5.9. Leaf number (plant$^{-1}$)

Leaf number plant$^{-1}$ increased up to 61 DAS and declined thereafter. Results are presented in Figure 4.37. The relationship between leaf number and $N_2O$ emission are not significant in the present study.

### 4.5.10. Leaf area (cm$^2$ plant$^{-1}$)

Leaf area increased from 12 DAS to 68 DAS and thereafter declined. Varietal differences in leaf area were recorded in the present experiment (Table. 4.19). Wheat varieties HUW 234 and DBW 14 showed higher leaf area compared to other varieties. However no significant relationship of leaf area with $N_2O$ emission was observed (Table 4.18).

### 4.5.11. Root length (cm plant$^{-1}$)

Root lengths of the varieties increased gradually from 12 DAS onwards and maximum were observed at 89 DAS and thereafter root length declined (Fig. 4.38). The observed correlation between $N_2O$ emission and root length is not significant.

### 4.5.12. Root volume (ml plant$^{-1}$)

The results of root volume are presented in Figure 4.39. The relationship between $N_2O$ emission and root volume in the present study is not significant.

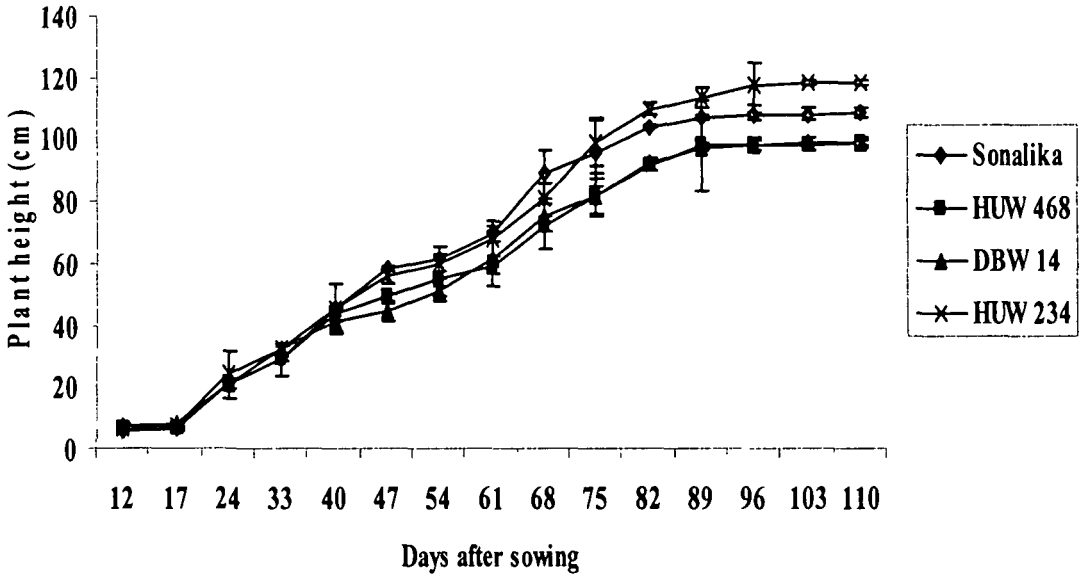


**Fig. 4.35. Plant height (cm) of wheat varieties in irrigated ecosystem. Vertical bars represent standard error of three replications.**

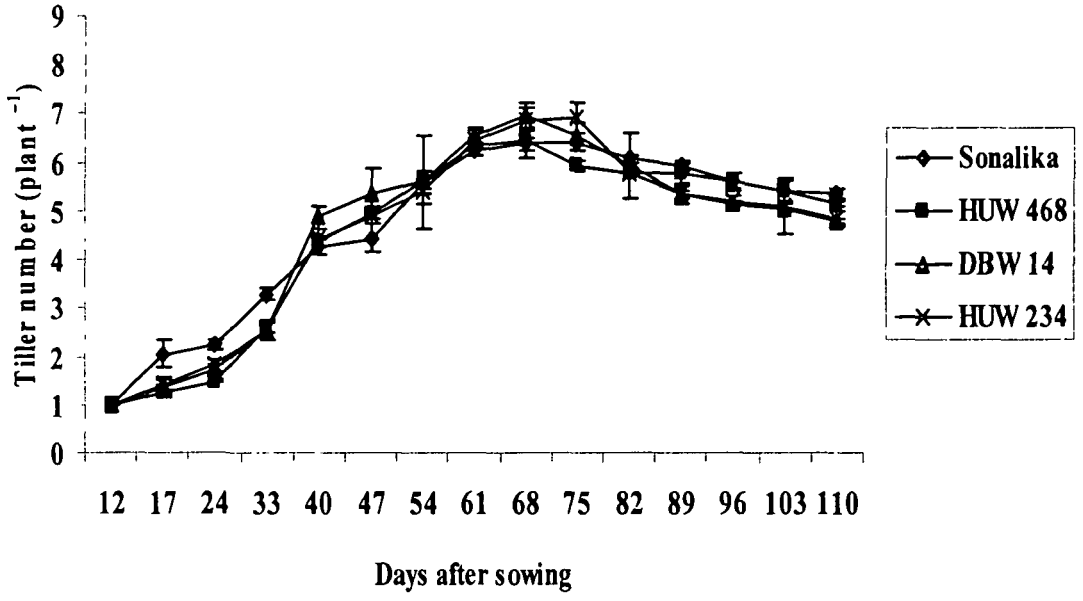


**Fig. 4.36. Tiller number (plant$^{-1}$) of wheat varieties in irrigated ecosystem. Vertical bars represent standard error of three replications.**

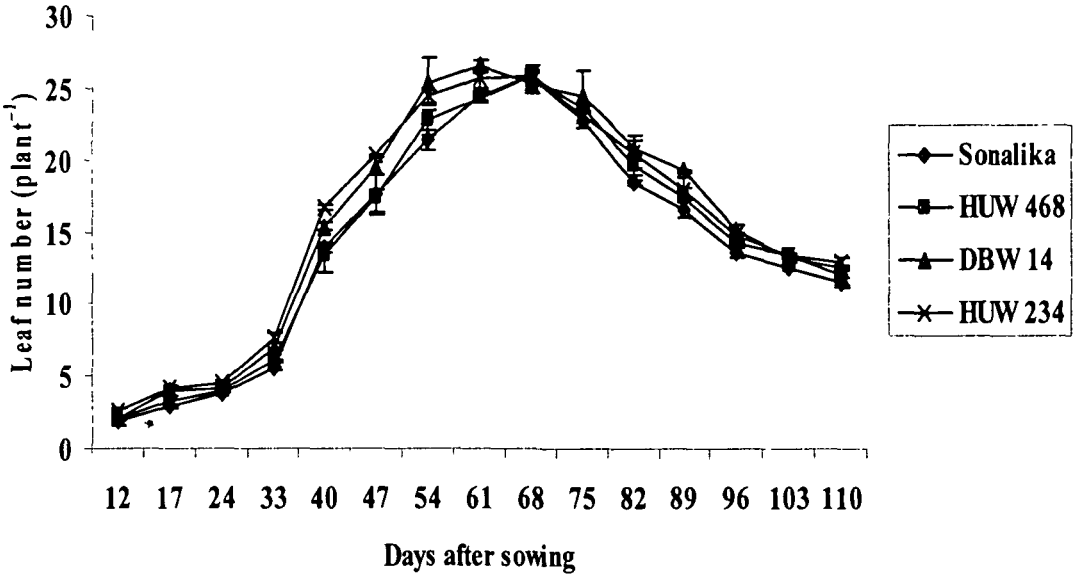


**Fig. 4.37. Leaf number (plant$^{-1}$) of wheat varieties in irrigated ecosystem. Vertical bars represent standard error of three replications.**

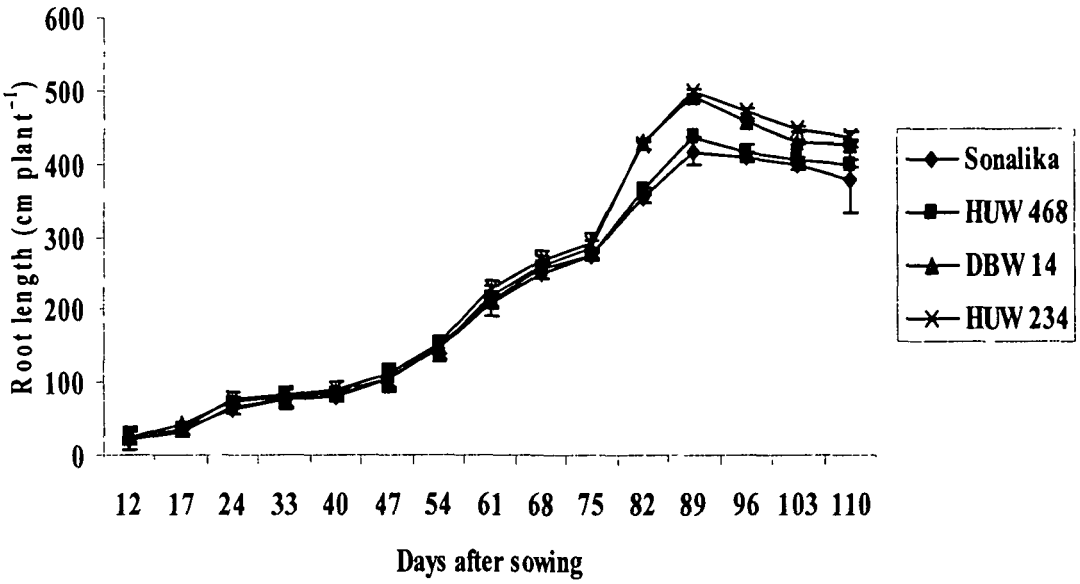


**Fig. 4.38. Root length (cm plant$^{-1}$) of wheat varieties in irrigated ecosystem. Vertical bars represent standard error of three replications.**

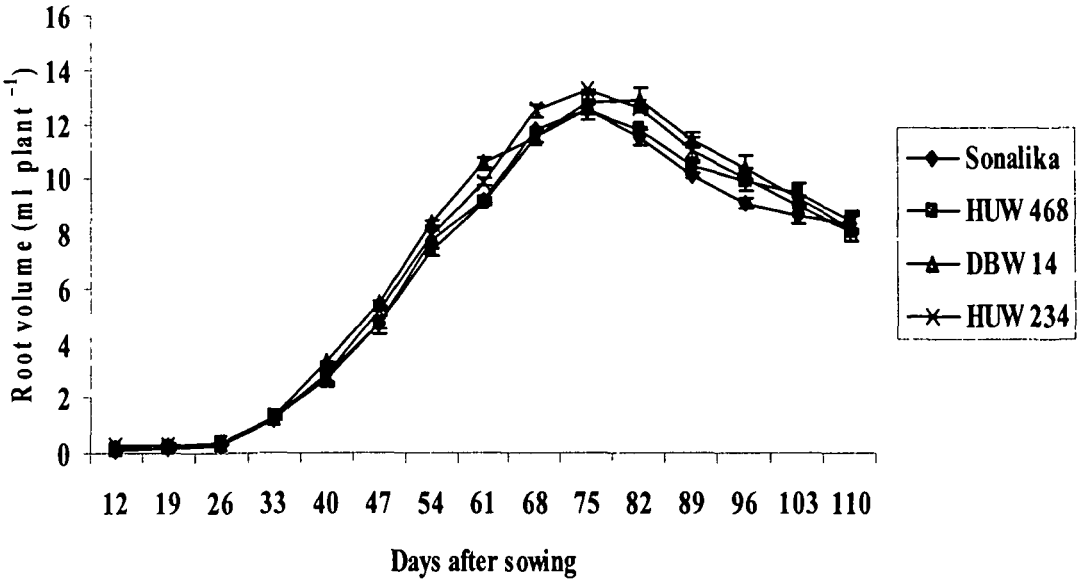


**Fig. 4.39. Root volume (ml plant$^{-1}$) of wheat varieties in irrigated ecosystem. Vertical bars represent standard error of three replications.**

### 4.5.13. Shoot dry weight (g plant$^{-1}$)

Shoot dry weight increased from 12 DAS onwards and it was maximum at 103 DAS (Table 4.19). Higher shoot dry weight was recorded in HUW 234 and DBW 14 at different growth stages. Shoot dry weight varies within varieties. The observed correlation between $N_2O$ emission and shoot dry weight is not significant (Table 4.18).

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### 4.5.14. Root dry weight (g plant$^{-1}$)

Root dry weights increased gradually from 12 DAS and declined at crop maturity stage (Table 4.19). The observed correlation between $N_2O$ emission and shoot dry weight is not significant.

### 4.5.15. Transpirational rates (mmol $H_2O$ $m^{-2}$ $s^{-1}$)

Table 4.19 represents the transpirational rates of wheat varieties. The rate of transpiration at different growth stages varied within the varieties. High $N_2O$ emitting varieties HUW 234 and DBW 14 showed higher transpirational rate compared to low emitting varieties. The rate of transpiration showed significant positive correlation with $N_2O$ emission (Table 4.18).

### 4.5.15. Yield and yield attributing parameters

Yield and yield attributing characteristics of wheat varieties are presented in Table 4.20. Wheat varieties DBW 14 and Sonalika recorded maximum yield of 32.26 q ha $^{-1}$ and 31.76 q ha $^{-1}$, respectively. Thousand grain weights of 55.78g, 55.06g, 50.34g and 45.13g were recorded in DBW 14, Sonalika, HUW 468 and HUW 234,

respectively. HUW 468 recorded higher grain sterility in terms of unfilled grains, although it had higher panicle length. It was observed that DBW 14 and Sonalika had higher panicle number per unit land area (square meter). The results are accepted for publication in *J. of Plant Research*, 2011, DOI: 10.1007/s10265-011-0464-4, in press.

**Table 4.18. Correlation of plant and soil parameters with nitrous oxide emission during irrigated wheat growing season.**

| Parameters | Correlation with nitrous oxide emission |
|---|---|
| Organic carbon (%) | 0.669** |
| Soil $NO_3^-$ - N (kg $ha^{-1}$) | 0.645** |
| Soil temperature ($^oC$) | 0.688** |
| Soil moisture (%) | $-0.013^{NS}$ |
| Soil pH | $0.459^{NS}$ |
| Leaf area ($cm^2$ $hill^{-1}$) | $0.090^{NS}$ |
| Leaf number($hill^{-1}$) | $0.111^{NS}$ |
| Root length (cm $hill^{-1}$) | $0.161^{NS}$ |
| Root volume (ml $hill^{-1}$) | $0.107^{NS}$ |
| Root dry weight (g $hill^{-1}$) | $0.115^{NS}$ |
| Shoot dry weight (g $hill^{-1}$) | $0.072^{NS}$ |
| Plant height (cm) | $0.184^{NS}$ |
| Tiller number ($hill^{-1}$) | $0.144^{NS}$ |
| Transpiration rate | 0.672** |

**Correlation is significant at the 0.01 level of significance

$^{NS}$Non- significant

**Table 4.19. Variations in leaf area, shoot dry weight, root dry weight and transpiration rate within wheat varieties compared by one-way ANOVA in irrigated wheat ecosystem. In each column, values with the similar letters are not significantly different at $P< 0.05$ level by Duncan's multiple range test.**

| | Days after sowing | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 19 | 26 | 33 | 40 | 47 | 54 | 61 | 68 | 75 | 82 | 89 | 96 | 103 | 110 |
| **Leaf area ($cm^2$ $hill^{-1}$)** | | | | | | | | | | | | | | | |
| **Sonalika** | 17.90a | 24.91b | 41.67a | 147.99b | 210.98d | 406.19d | 698.48c | 749.89c | 777.90a | 743.91c | 639.33b | 554.97ab | 493.90a | 374.21b | 364.16c |
| **HUW 468** | 17.60a | 22.54b | 28.65a | 145.53b | 293.38a | 448.09c | 684.85d | 729.24d | 766.27b | 755.87b | 619.97c | 509.94b | 396.10b | 369.91b | 365.18c |
| **HUW 234** | 17.70a | 35.38a | 34.48a | 121.63b | 255.68c | 516.31b | 714.58b | 771.44b | 775.49a | 762.47b | 644.83b | 529.75ab | 452.07a | 428.51a | 420.21a |
| **DBW 14** | 18.63a | 31.65a | 32.61a | 211.05a | 280.84b | 545.24a | 739.92a | 786.15a | 780.88a | 773.51a | 667.65a | 590.91a | 488.21a | 424.08a | 409.33b |
| **CD-5%** | 1.69 | 5.13 | 26.66 | 32.91 | 11.67 | 4.13 | 11.10 | 9.68 | 8.90 | 8.94 | 7.21 | 68.06 | 52.99 | 8.86 | 6.73 |
| **Shoot dry weight (g $hill^{-1}$)** | | | | | | | | | | | | | | | |
| **Sonalika** | 0.14c | 0.18b | 0.22c | 0.73b | 0.96b | 1.90c | 3.28b | 5.51c | 6.76b | 7.51c | 8.60c | 9.52b | 10.27b | 10.37b | 10.24a |
| **HUW 468** | 0.19b | 0.21ab | 0.32b | 0.56d | 0.83c | 1.81c | 3.21b | 5.16d | 6.13c | 7.08d | 8.17d | 9.14c | 10.06b | 10.59ab | 9.72a |
| **HUW 234** | 0.15c | 0.25a | 0.33b | 0.64c | 1.26a | 2.19b | 3.99a | 5.80b | 6.97ab | 8.03b | 9.03b | 10.37a | 11.10a | 11.17ab | 10.28a |
| **DBW 14** | 0.23a | 0.26a | 0.54a | 0.81a | 1.32a | 3.03a | 4.07a | 6.04a | 7.08a | 8.65a | 9.97a | 10.44a | 11.49a | 11.64a | 10.79a |
| **CD-5%** | 0.02 | 0.05 | 0.04 | 0.06 | 0.07 | 0.12 | 0.11 | 0.13 | 0.22 | 0.16 | 0.07 | 0.24 | 0.63 | 1.07 | 1.38 |
| **Root dry weight (g $hill^{-1}$)** | | | | | | | | | | | | | | | |
| **Sonalika** | 0.06ab | 0.06b | 0.07b | 0.12ab | 0.60b | 1.47b | 2.25a | 2.52a | 3.32a | 3.63a | 4.36ab | 4.45b | 4.55a | 4.15c | 3.92c |
| **HUW 468** | 0.04b | 0.04c | 0.07b | 0.10b | 0.51c | 1.54b | 2.11a | 2.41a | 2.85b | 3.48a | 4.16b | 4.39b | 4.53a | 4.37bc | 4.16bc |
| **HUW 234** | 0.06ab | 0.08ab | 0.09b | 0.15ab | 0.67a | 1.88a | 2.24a | 2.66a | 3.56a | 3.81a | 4.48ab | 4.85a | 4.91a | 4.58ab | 4.39ab |
| **DBW 14** | 0.07a | 0.09a | 0.12a | 0.18a | 0.61b | 1.90a | 2.49a | 2.81a | 3.73a | 4.16a | 4.76a | 4.95a | 5.05a | 4.72a | 4.48a |
| **CD-5%** | 0.03 | 0.02 | 0.03 | 0.06 | 0.05 | 0.19 | 0.45 | 0.53 | 0.42 | 0.73 | 0.44 | 0.29 | 0.62 | 0.33 | 0.30 |
| **Transpiration rate (mmol $H_2O$ $m^{-2}$ $s^{-1}$)** | | | | | | | | | | | | | | | |
| **Sonalika** | 0.16a | 1.15c | 6.18d | 6.35d | 5.87c | 10.10c | 4.88c | 5.76b | 5.71d | 6.03d | 10.43c | 6.09d | 7.78c | 7.13c | 7.08c |
| **HUW 468** | 0.16a | 1.21b | 6.38c | 6.40c | 6.15a | 10.33b | 5.85a | 6.13a | 6.19b | 6.87c | 10.89b | 7.13c | 7.76c | 6.76d | 6.73d |
| **HUW 234** | 0.17a | 1.26a | 6.51a | 6.58a | 6.17a | 10.73a | 4.96b | 6.11a | 6.11c | 9.82a | 11.13a | 7.38b | 10.47b | 7.62b | 7.61a |
| **DBW 14** | 0.15a | 1.12c | 6.48b | 6.55b | 5.98b | 10.67a | 5.81a | 6.12a | 6.26a | 9.72b | 11.11a | 7.45a | 10.57a | 7.66a | 7.54b |
| **CD-5%** | 0.02 | 0.04 | 0.02 | 0.04 | 0.03 | 0.13 | 0.05 | 0.06 | 0.03 | 0.04 | 0.09 | 0.05 | 0.08 | 0.01 | 0.04 |

**Table 4.20. Yield and yield attributing parameters of wheat varieties and seasonal integrated nitrous oxide emission flux ($E_{sif}$) in irrigated wheat ecosystem. In each column, values with the same letters are not significantly different at $P<0.05$ level by Duncan's multiple range test.**

| Wheat varieties/ parameters | Panicle square meter$^{-1}$ | Panicle length (cm) | Sterility (%) | Thousand grain weight (g) | Yield (q ha$^{-1}$) | $E_{sif}$ (mg $N_2O$-N $m^{-2}$) |
|---|---|---|---|---|---|---|
| Sonalika | 241.31b | 13.77b | 11.96b | 55.06 a | 31.76 a | 325.24d |
| HUW 468 | 224.47d | 15.90a | 13.66a | 50.34 b | 29.00 b | 339.02c |
| HUW 234 | 235.75 c | 12.67b | 12.11b | 45.13 c | 29.22 b | 380.91a |
| DBW 14 | 244.27a | 12.73b | 11.00 c | 55.78 a | 32.26 a | 375.48b |

## 4.6. Nitrous oxide emission estimation from autumn rice (*Ahu*) ecosystem with different doses of fertilizer combinations

### 4.6.1. Meteorological parameters

Meteorological parameters recorded during experimental period are presented in Figure 3.6. Maximum temperature of 33.0°C was recorded in July, 2008. The minimum temperature of 18.50°C was recorded in the month of April, 2008. Maximum rainfall was recorded in the month of June.

### 4.6.2. Nitrous oxide flux (μg $N_2O$-N $m^{-2}$ $h^{-1}$)

$N_2O$ flux of 41 and 50 μg $N_2O$-N $m^{-2}$ $h^{-1}$ was observed in varieties Phorma and Luit, respectively (Fig. 4.40 and 4.41) at transplanting (0 DAT). The rate of emission was lower in varieties up to 28 days after transplanting irrespective of the treatments. The mean $N_2O$ flux increased from 62 μg $N_2O$-N $m^{-2}$ $h^{-1}$ at 28 DAT to 146 μg $N_2O$-N $m^{-2}$ $h^{-1}$ at 35 DAT in Phorma. In Luit mean flux increased from 47 μg $N_2O$-N $m^{-2}$ $h^{-1}$ at 28 DAT to 125 μg $N_2O$-N $m^{-2}$ $h^{-1}$ at 35 DAT. Again at 49 DAT elevated $N_2O$ fluxes were observed in both the varieties. Maximum flux values of 280 μg $N_2O$-N $m^{-2}$ $h^{-1}$ and 209 μg $N_2O$-N $m^{-2}$ $h^{-1}$ was observed in $T_9$ at 49 DAT in variety Phorma and Luit, respectively. From 49 DAT to 63 DAT a decreasing trend in $N_2O$ emission was observed in both the varieties. Further, at 70 DAT mean $N_2O$ fluxes increased up to 109 μg $N_2O$-N $m^{-2}$ $h^{-1}$ in Phorma and 70 μg $N_2O$-N $m^{-2}$ $h^{-1}$ in Luit, respectively. $N_2O$ emission decreased in both the varieties at harvest. Seasonal integrated nitrous oxide emission ($E_{sif}$) recorded in variety Phorma treated with different fertilizer levels are-$T_1$ (175.56 mg $N_2O$-N $m^{-2}$), $T_2$ (169.34 mg $N_2O$-N $m^{-2}$), $T_3$ (179.81 mg $N_2O$-N $m^{-2}$), $T_4$ (190.28 mg $N_2O$-N $m^{-2}$), $T_5$ (192.86 mg $N_2O$-N $m^{-2}$), $T_6$ (196.84 mg $N_2O$-N $m^{-2}$), $T_7$ (212.29 mg $N_2O$-N $m^{-2}$), $T_8$ (205.46 mg $N_2O$-N $m^{-2}$) and $T_9$ (224.05 mg $N_2O$-N $m^{-2}$). Whereas $E_{sif}$ values recorded in Luit are -$T_1$ (118.94 mg $N_2O$-N $m^{-2}$), $T_2$ (117.54 mg $N_2O$-N $m^{-2}$), $T_3$ (121.85 mg $N_2O$-N $m^{-2}$), $T_4$ (162.79 mg $N_2O$-N $m^{-2}$), $T_5$ (161.61 mg

$N_2O$-N $m^{-2}$), $T_6$ (168.67 mg $N_2O$-N $m^{-2}$), $T_7$ (179.98 mg $N_2O$-N $m^{-2}$), $T_8$ (177.74 mg $N_2O$-N $m^{-2}$) and $T_9$ (182.16 mg $N_2O$-N $m^{-2}$). The $E_{sif}$ values are presented in Table 4.28. Significant variations in $E_{sif}$ values are observed within treatments. Both the varieties showed higher seasonal emission in treatment, N, $P_2O_5$, $K_2O$ @ 45:22:22 kg $ha^{-1}$ in the form of Urea, SSP, MOP + FYM ($T_9$). Whereas, lowest emission was recorded when rice varieties were grown in N, $P_2O_5$, $K_2O$ @ 35:18:18 kg $ha^{-1}$ in the form of Urea, SSP, MOP ($T_2$). Variety Phorma showed higher seasonal emission compared to Luit (Table 4.28 ).

### 4.6.3. Water level (cm)

Figure 4.42 represents the water level of the experimental field with variety Phorma and Luit treated with different fertilizers. The standing water level at the time of transplanting (0 DAT) in the treated plots varied between 3 cm to 4 cm. Significant drop in water level was observed at 35 and 49 DAT. We could not obtain a significant relationship between and $N_2O$ emissions and field water level (Table 4.21).

### 4.6.4. Soil temperature ($^oC$)

Figure 4.43 represents the soil temperature of the experimental field with variety Phorma and Luit. Soil temperature gradually increased from 7 DAT onwards and maximum soil temperature was recorded at 49 DAT. The observed relationship between soil temperature and $N_2O$ emission are not significant (Table 4.21).

### 4.6.5. Soil organic carbon (%)

Figure 4.44 and 4.45 represents the soil organic carbon of the experimental field with these two varieties subjected to various fertilizer treatments. Soil organic

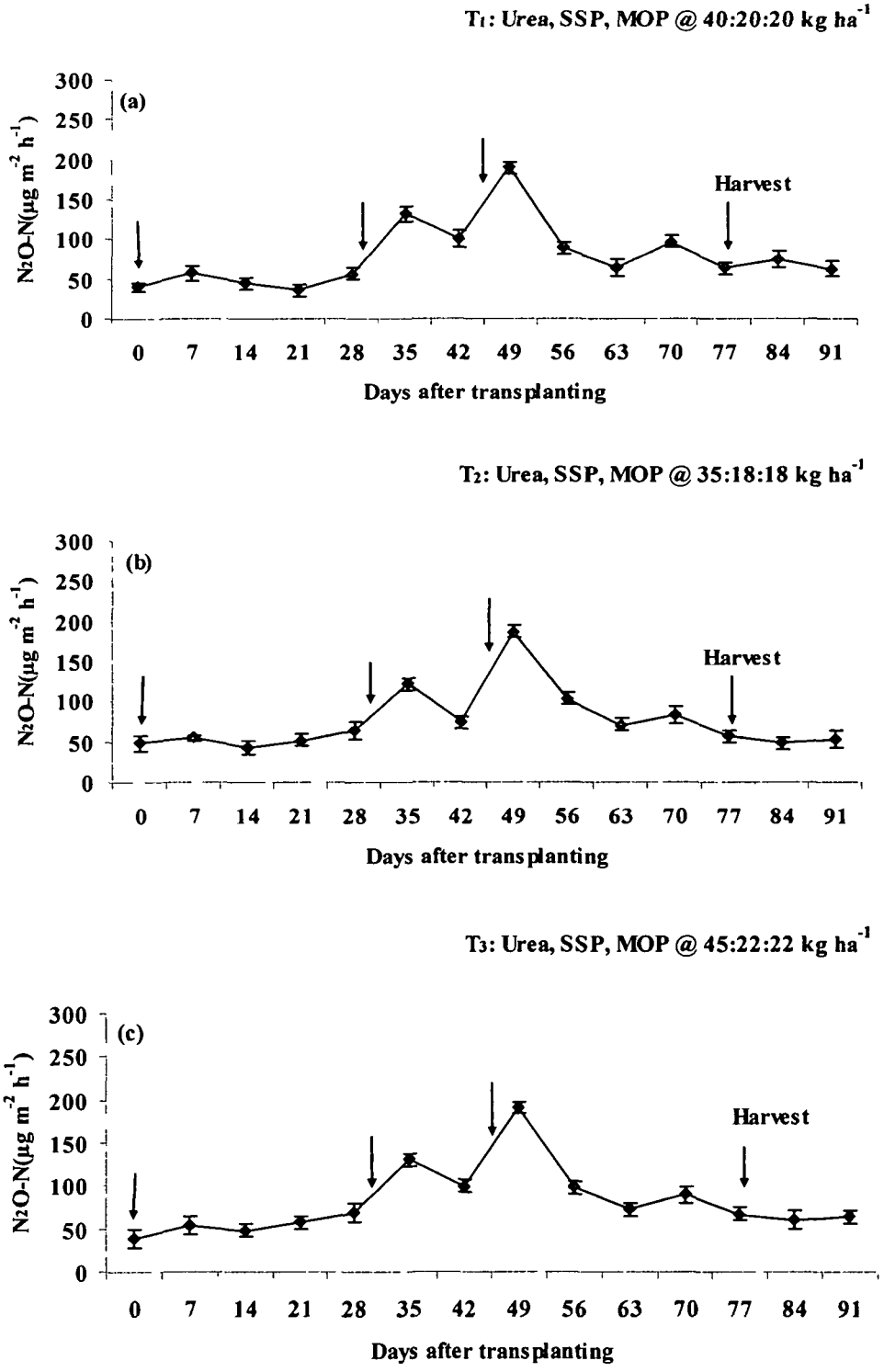


Fig. 4.40. (a), (b) and (c). Nitrous oxide fluxes $N_2O$-N (µg $m^{-2}$ $h^{-1}$) from rice variety Phorma grown at fertilizer treatments $T_1$, $T_2$ and $T_3$, respectively. Vertical bars represent standard error of three replications. The arrows indicate the time of application of fertilizer and day of harvest.

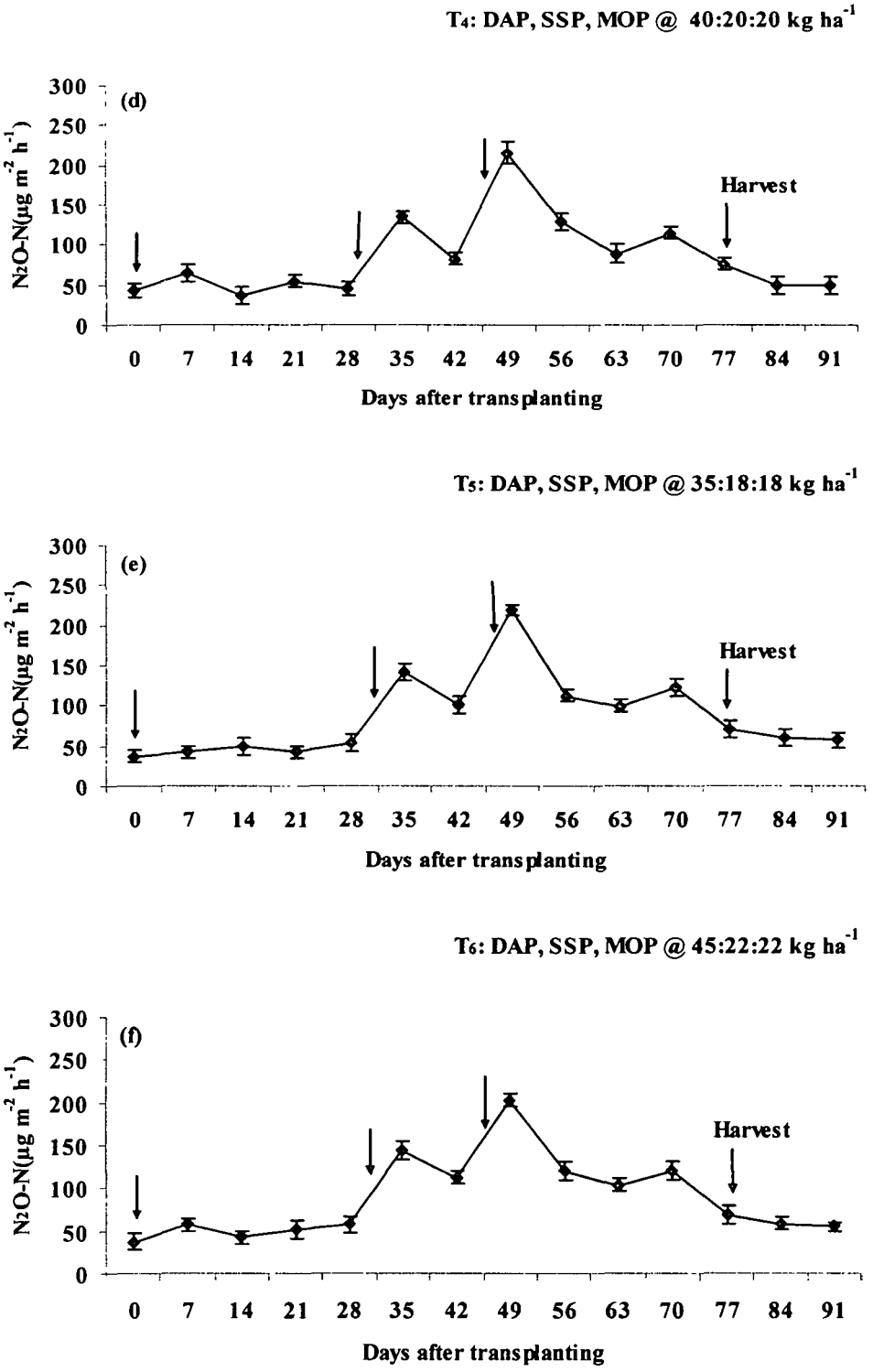


**Fig. 4.40. (d), (e) and (f). Nitrous oxide fluxes $N_2O$-N (µg $m^{-2}$ $h^{-1}$) from rice variety Phorma grown at fertilizer treatments $T_4$, $T_5$ and $T_6$, respectively. Vertical bars represent standard error of three replications. The arrows indicate the time of application of fertilizer and day of harvest.**

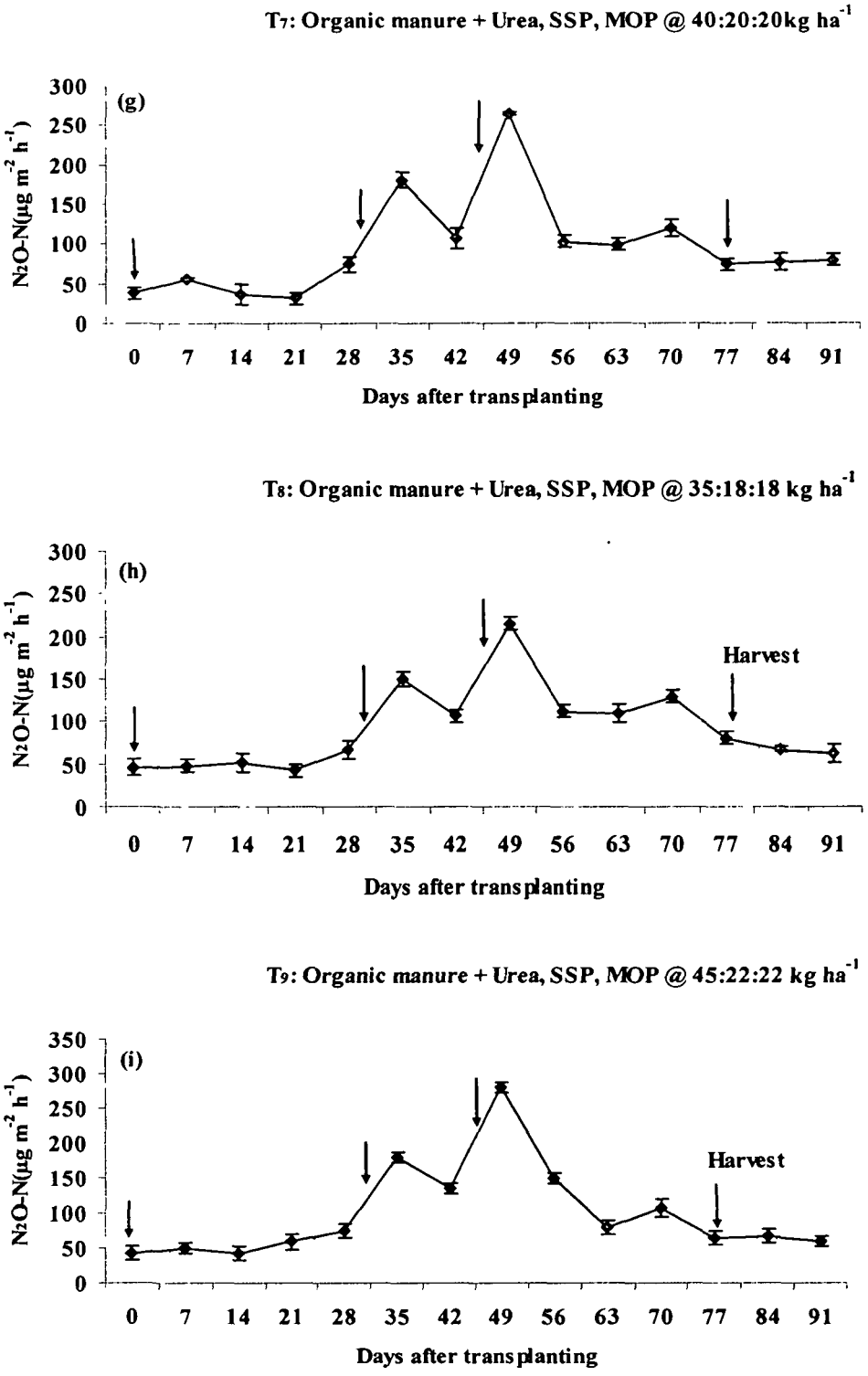


Fig. 4.40. (g), (h) and (i). Nitrous oxide fluxes $N_2O$-N ($\mu g\ m^{-2}\ h^{-1}$) from rice variety Phorma grown at fertilizer treatments $T_7$, $T_8$ and $T_9$, respectively. Vertical bars represent standard error of three replications. The arrows indicate the time of application of fertilizer and day of harvest.

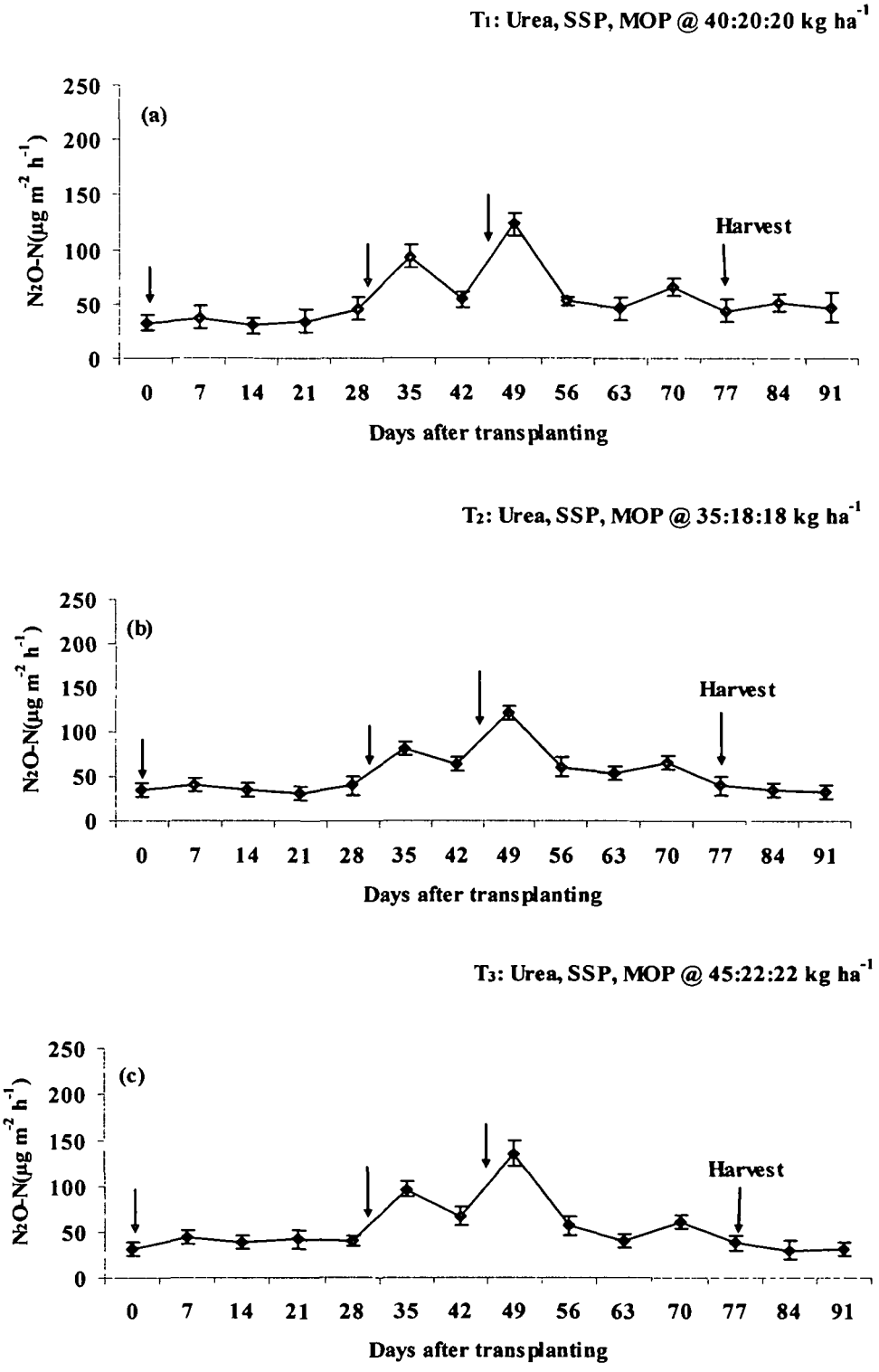


**Fig. 4.41. (a), (b) and (c). Nitrous oxide fluxes $N_2O$-N (µg $m^{-2}$ $h^{-1}$) from rice variety Luit grown at fertilizer treatments $T_1$, $T_2$ and $T_3$, respectively. Vertical bars represent standard error of three replications. The arrows indicate the time of application of fertilizer and day of harvest.**

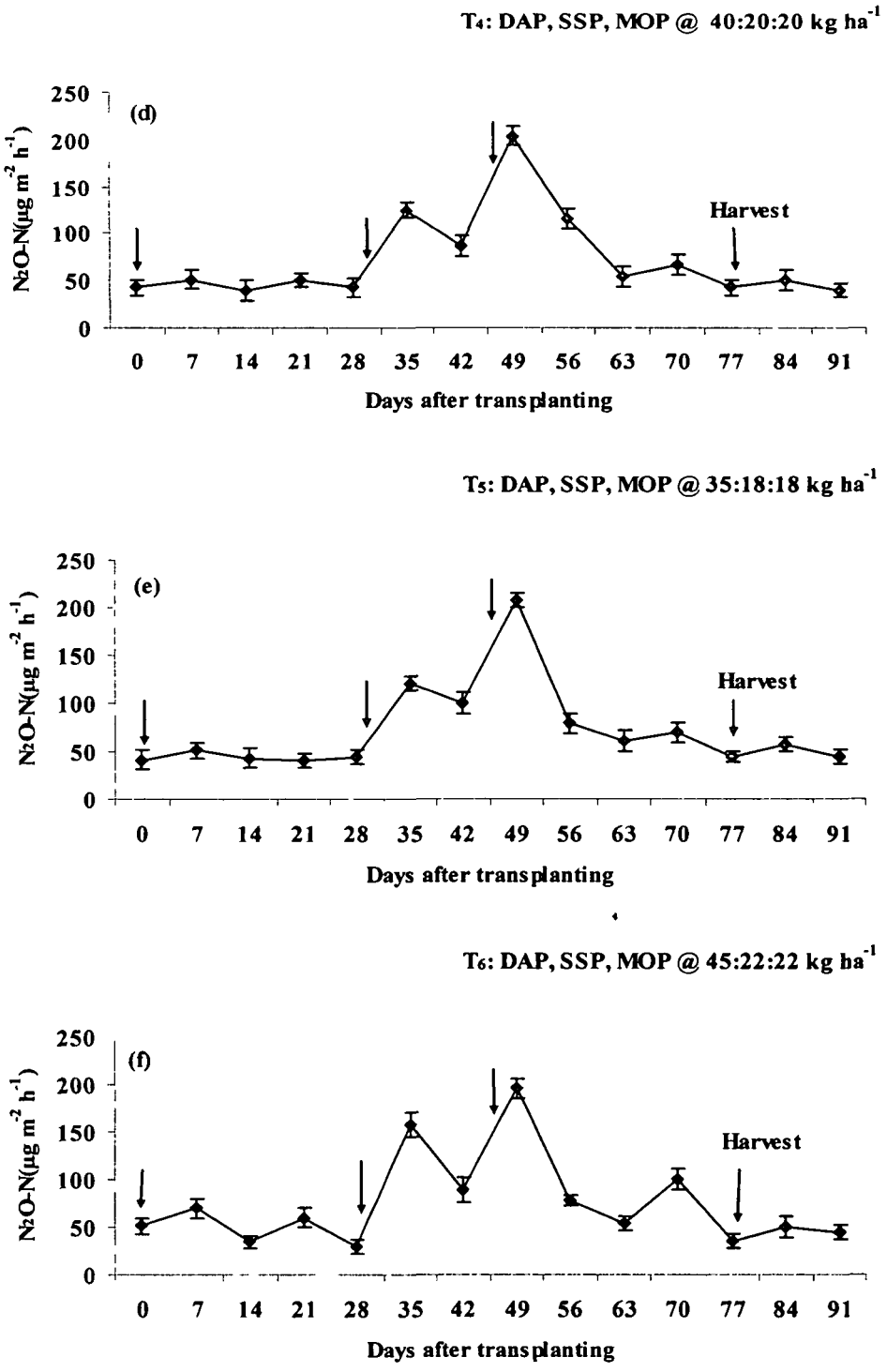


**Fig. 4.41. (d), (e) and (f). Nitrous oxide fluxes $N_2O$-N (µg $m^{-2}$ $h^{-1}$) from rice variety Luit grown at fertilizer treatments $T_4$, $T_5$ and $T_6$, respectively. Vertical bars represent standard error of three replications. The arrows indicate the time of application of fertilizer and day of harvest.**

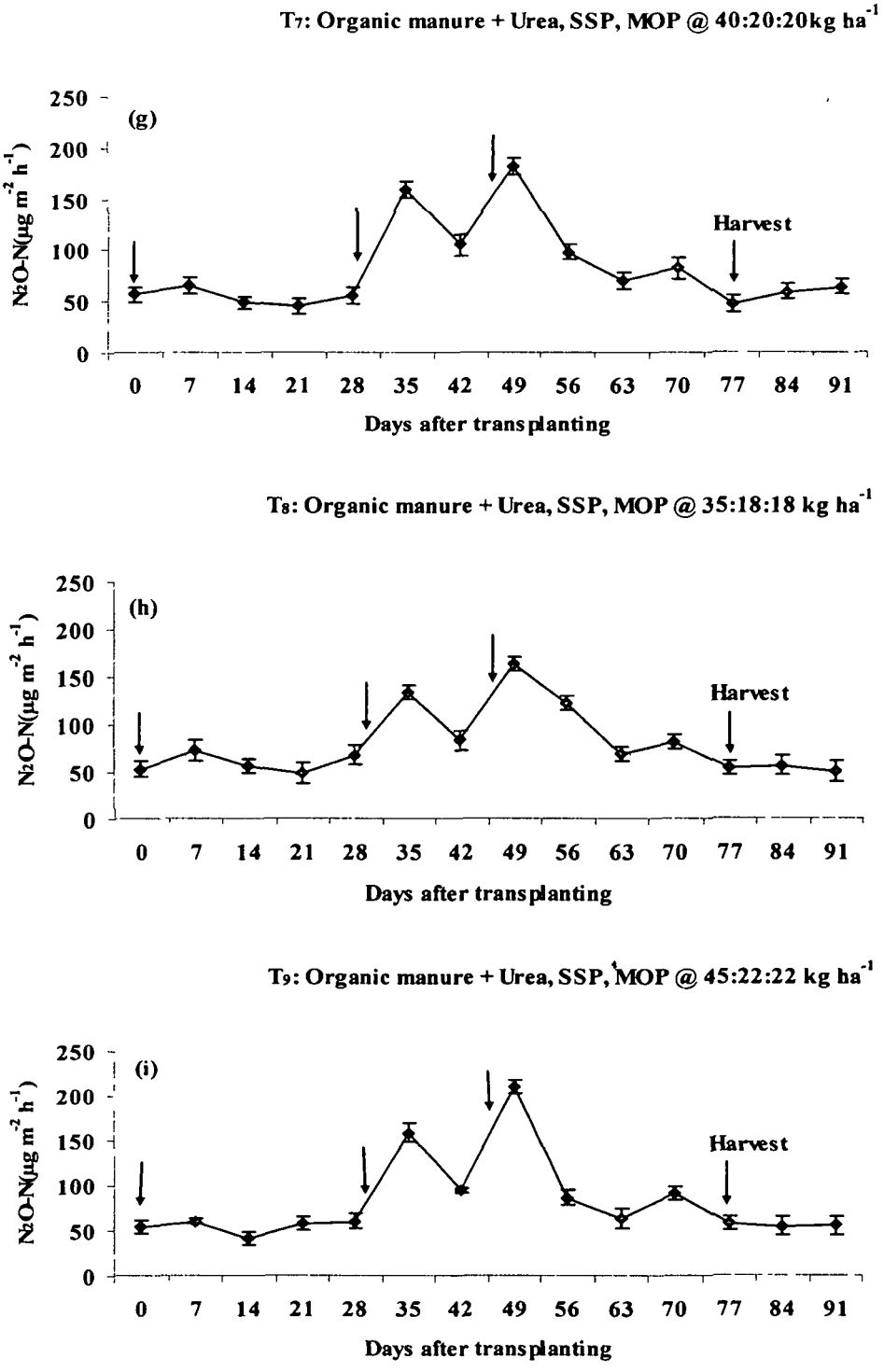


**Fig. 4.41. (g), (h) and (i). Nitrous oxide fluxes $N_2O$-N (µg $m^{-2}$ $h^{-1}$) from rice variety Luit grown at fertilizer treatments $T_7$, $T_8$ and $T_9$, respectively. Vertical bars represent standard error of three replications. The arrows indicate the time of application of fertilizer and day of harvest.**

carbon during the rice growing season varied from 0.90% to 1.22%. Soil organic carbons of the treated plots were initially low and increased during maximum tillering, panicle initiation and crop ripening stage. In both the varieties soil organic carbon varied within treatments. High soil organic carbon was observed in plots treated with $T_7$, $T_8$ and T9 in both the varieties. The relationship between soil organic carbon and $N_2O$ emission are found to be significant (Table 4.21).

### 4.6.6. Soil nitrate nitrogen

Figure 4.46 and 4.47 represents the soil $NO_3^-$-N of the experimental field with the variety Phorma and Luit grown at different level of fertilizers. Soil $NO_3^-$-N content was initially low and increased rapidly from 35 DAT onwards till crop ripening stage. In both the varieties soil $NO_3^-$ content varied within treatments. High soil $NO_3^-$ content was recorded in treatment $T_9$ followed by $T_7$ and $T_8$ in both the varieties. The soil $NO_3^-$-N content showed significant positive correlation with $N_2O$ emission (Table 4.21).

### 4.6.7. Soil pH

Soil pH during crop growing season varied in between 5.50 to 6.23 (Fig. 4.48) and variations within treatments were noticed. The relationship between $N_2O$ emission and soil pH in the present study is not significant (Table 4.21).

### 4.6.7. Plant height (cm)

Table 4.22 and 4.25 represents the plant heights of rice varieties Phorma and Luit, respectively. Recorded plant height in Phorma and Luit at 7 DAT were 25 cm to 28 cm and 19.1 cm to 19.9 cm. The relationship between $N_2O$ emission and plant height in the present study is not significant (Table 4.21).

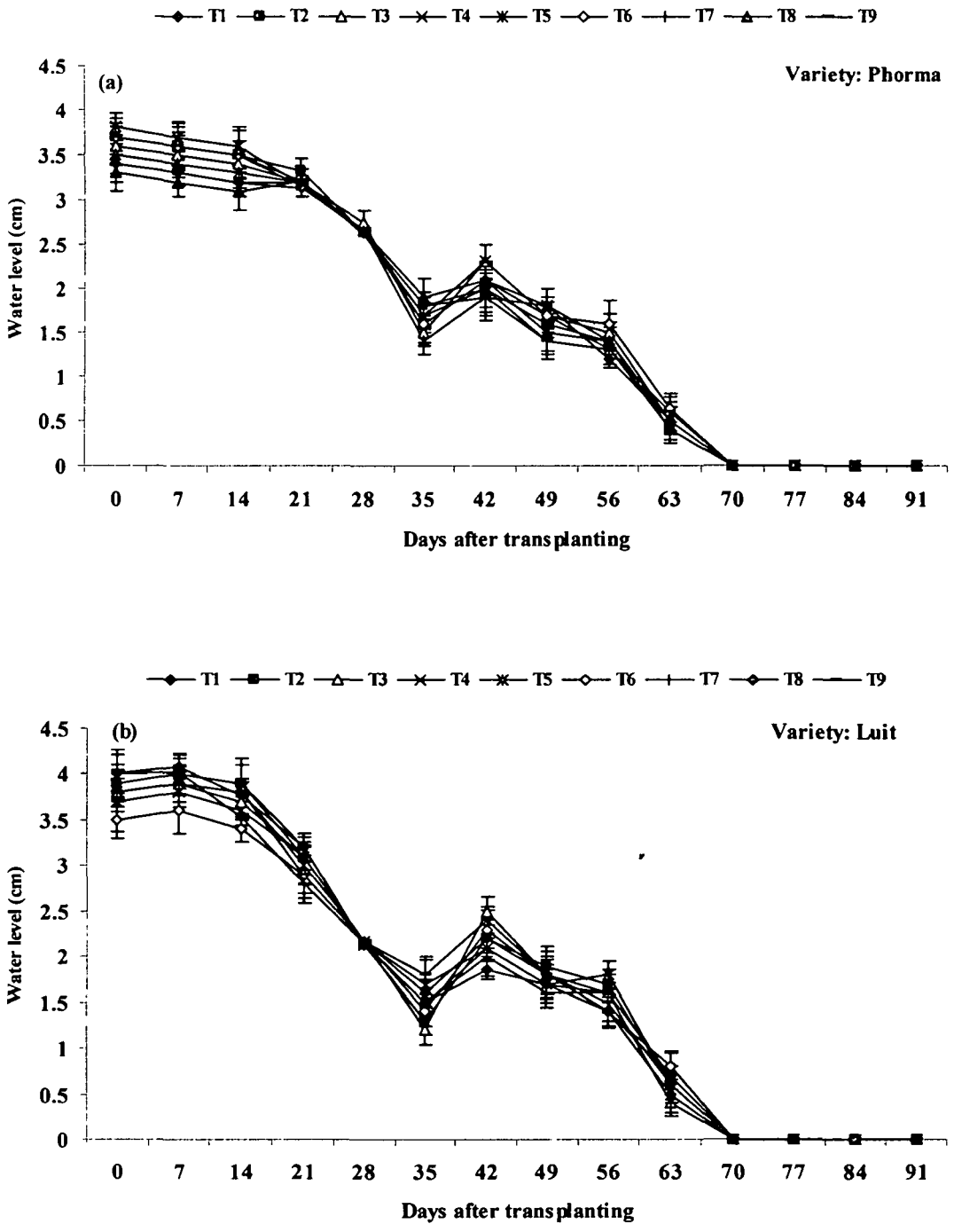


**Fig. 4.42. (a) and (b). Water level (cm) of the experimental field with rice variety Phorma and Luit, respectively. Vertical bars represent standard error of three replications.**

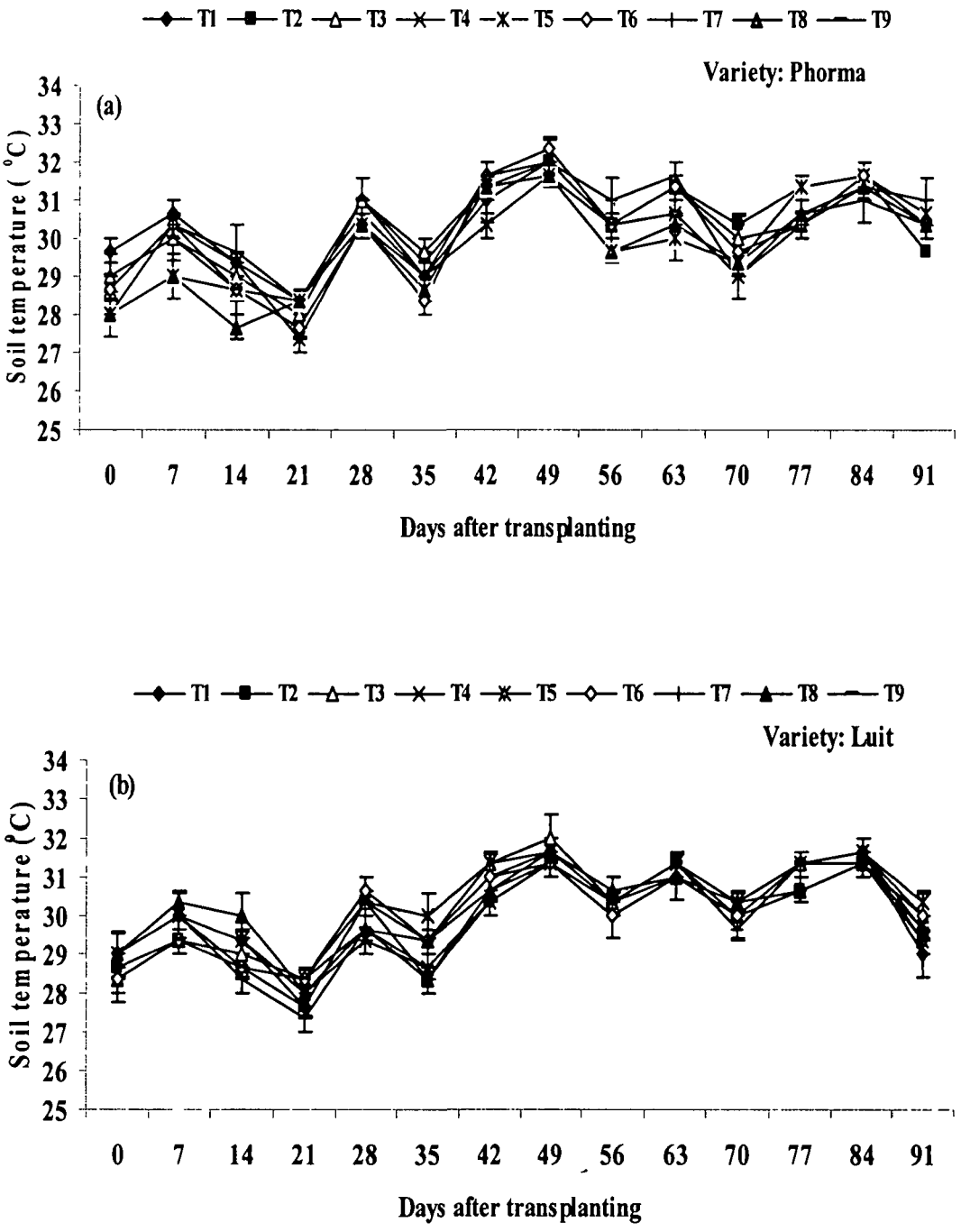


**Fig. 4.43. (a) and (b). Soil temperature ($^{o}$C) of the experimental field with rice variety Phorma and Luit, respectively. Vertical bars represent standard error of three replications.**

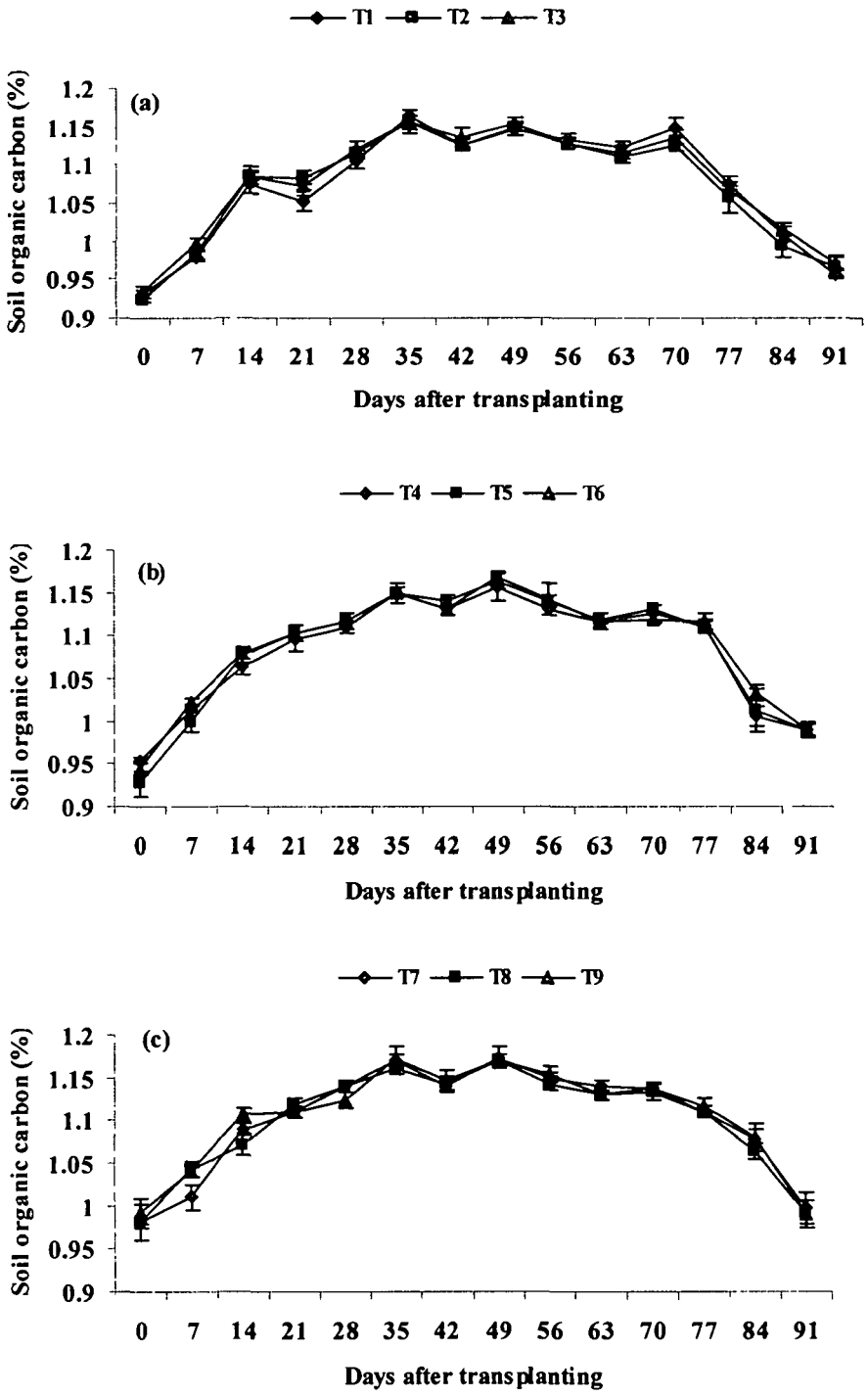


**Fig. 4.44. (a), (b) and (c) soil organic carbon (%) of the experimental field with rice variety Phorma under different fertilizer treatments. Vertical bars represent standard error of three replications.**

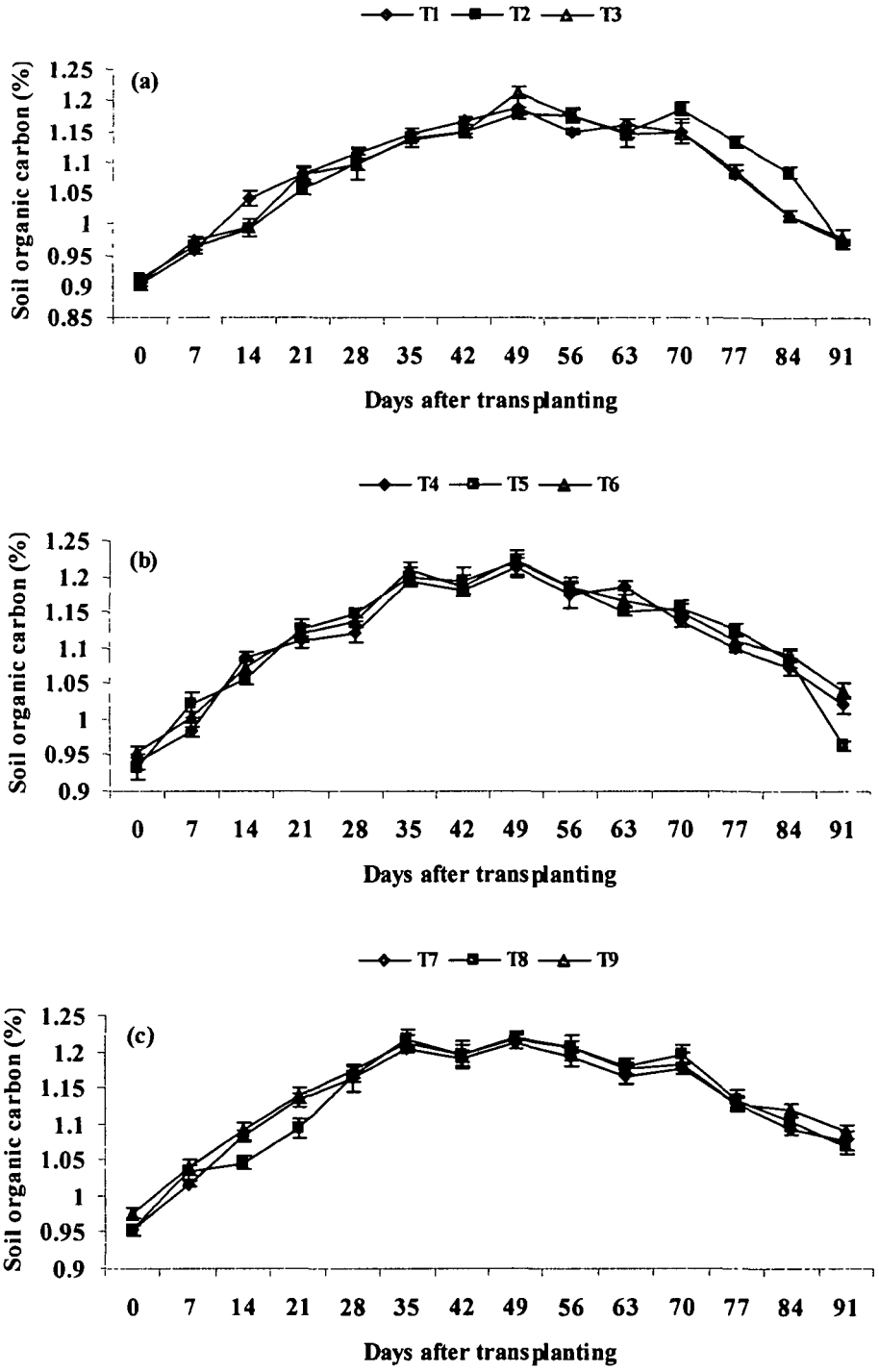


**Fig. 4.45. (a), (b) and (c) soil organic carbon (%) of the experimental field with rice variety Luit under different fertilizer treatments. Vertical bars represent standard error of three replications.**

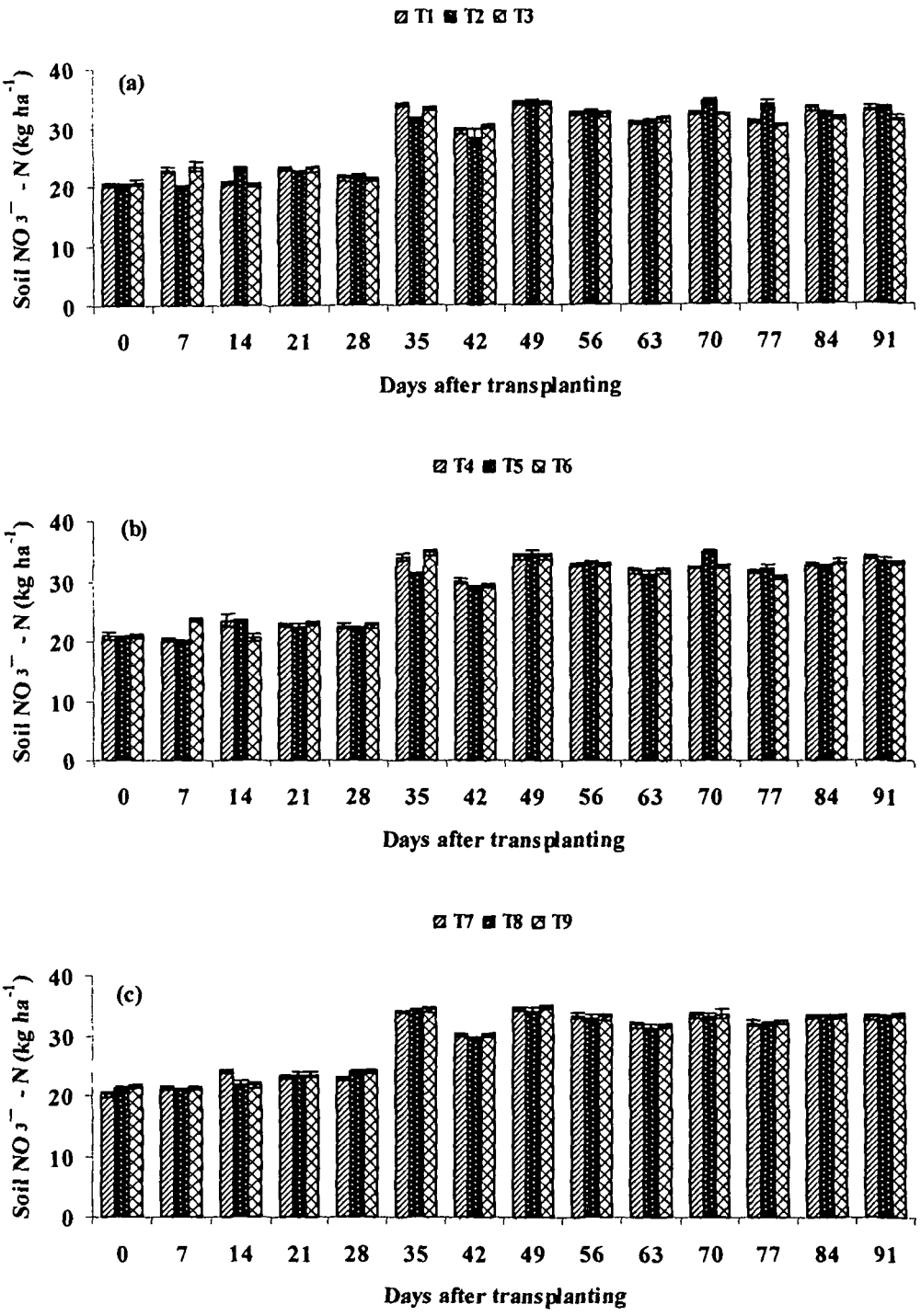


**Fig. 4.46. (a), (b) and (c) soil $NO_3^-$ - N (kg ha $^{-1}$) of the experimental field with rice variety Phorma under different fertilizer treatments. Vertical bars represent standard error of three replications.**

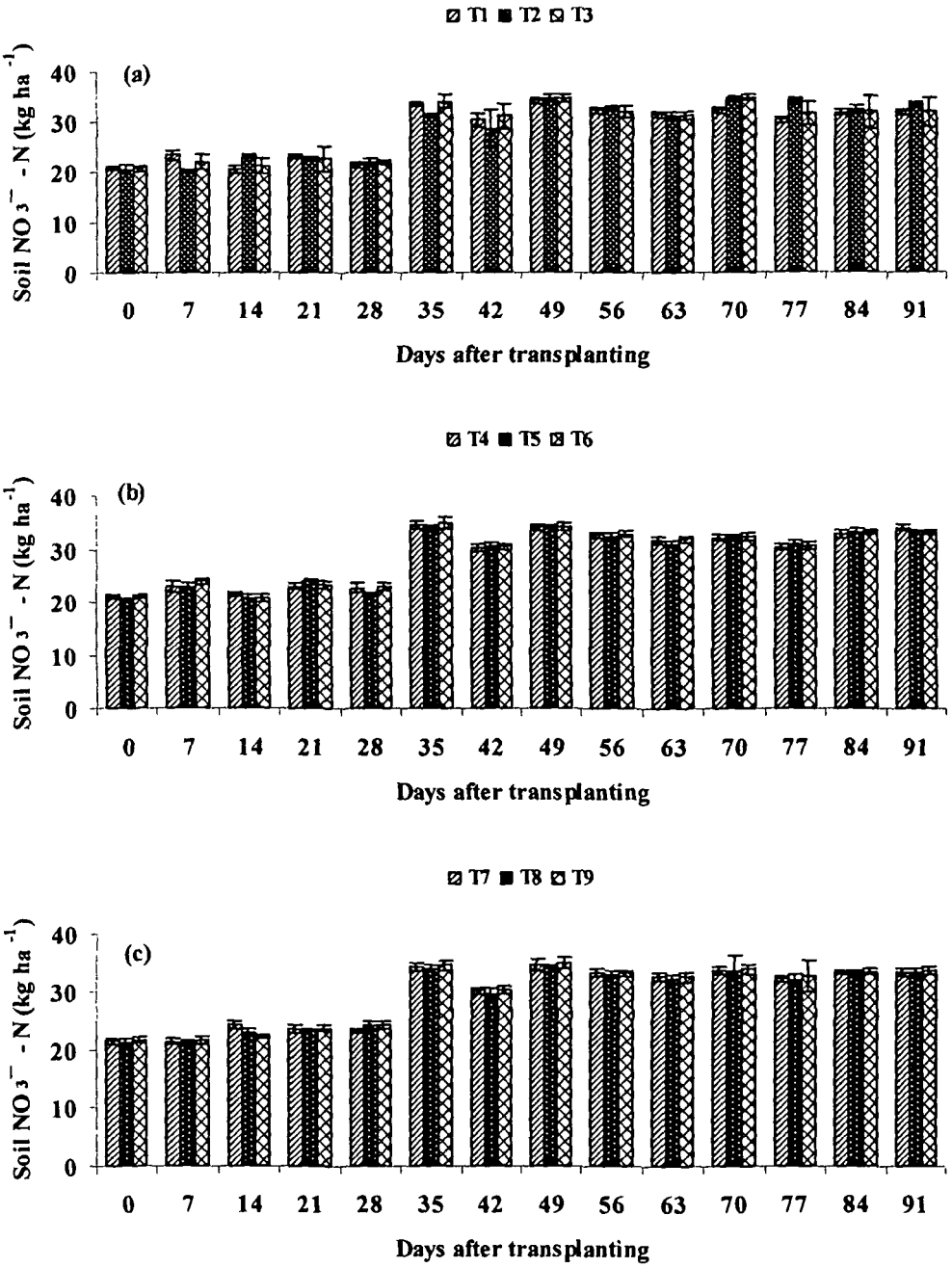


**Fig. 4.47. (a), (b) and (c) soil $NO_3^-$ - N (kg ha $^{-1}$) of the experimental field with rice variety Luit under different fertilizer treatments. Vertical bars represent standard error of three replications.**

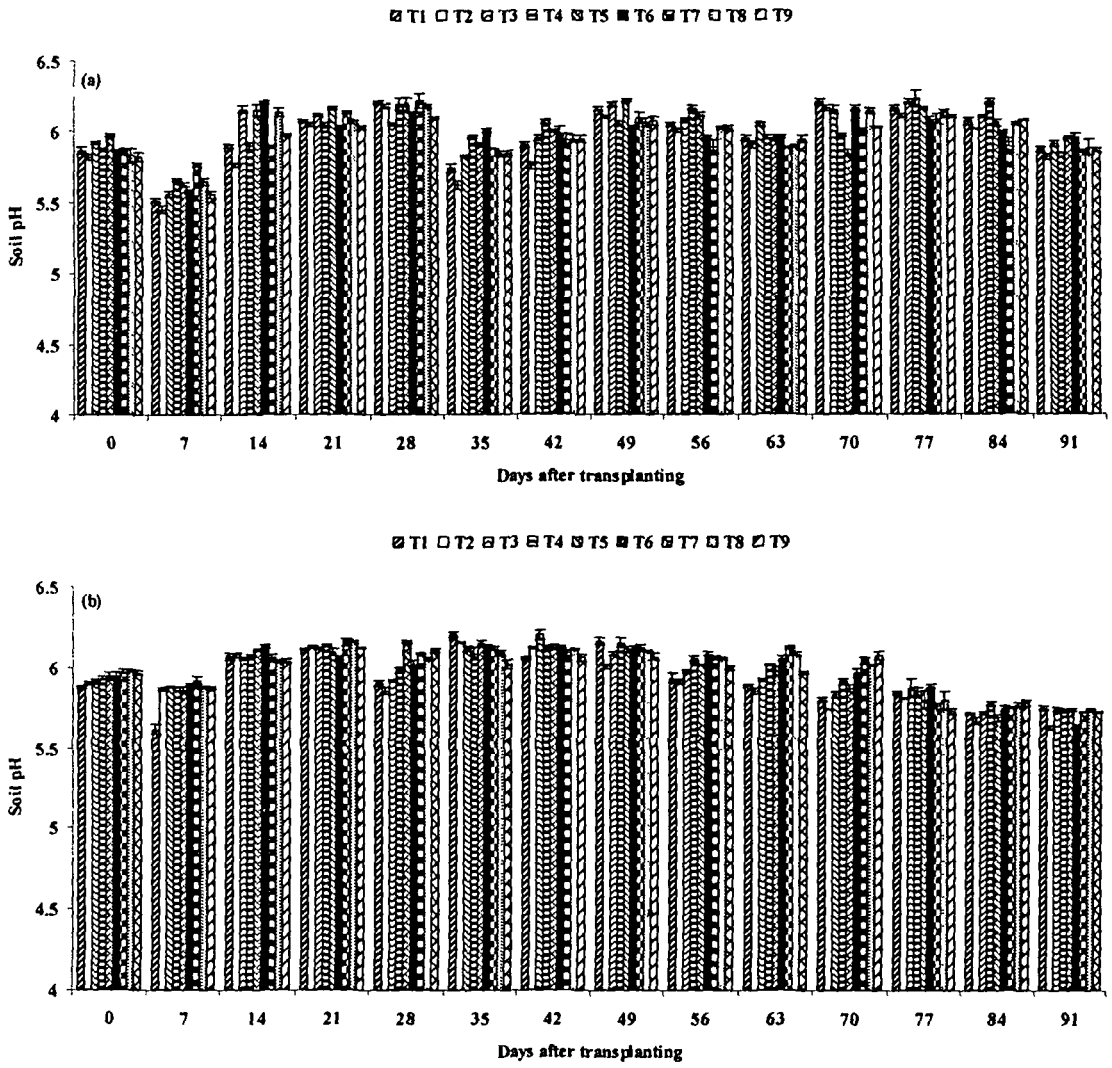


**Fig. 4.48. (a) and (b) soil pH of the experimental field with rice variety Phorma and Luit, respectively. Vertical bars represent standard error of three replications.**

### 4.6.8. Tiller number (hill$^{-1}$)

Table 4.22 and 4.25 represents the tiller numbers hill$^{-1}$ of rice varieties Phorma and Luit, respectively. Number of tillers increased up to 56 DAT in Phorma and 49 DAT in Luit and declined thereafter. Phorma showed comparatively higher tillers hill$^{-1}$ at different growth stages. Treatments were found to have some impact on tiller growth of the varieties. A significant relationship between $N_2O$ emission and tiller number was observed.

### 4.6.9. Leaf number (hill$^{-1}$)

Table 4.22 and 4.25 represents the leaf numbers hill$^{-1}$ of rice varieties Phorma and Luit, respectively. There was increase in leaf numbers of the varieties up to 63 DAT and thereafter declined. Leaf numbers varied within treated plots at different growth stages of the varieties. Leaf numbers of variety Phorma recorded significant positive correlations with $N_2O$ emission in present study.

### 4.6.10. Leaf area (cm$^2$ hill$^{-1}$)

Table 4.23 and 4.26 represents the leaf area (cm$^2$ hill$^{-1}$) of the rice varieties Phorma and Luit, respectively. Leaf area of the varieties increased up to 56 DAT and declined thereafter. Leaf area ranged from 939.97cm$^2$ to 946.84cm$^2$ and from 696.26cm$^2$ to 717.56cm$^2$ in Phorma and Luit, respectively at 56 DAT. The leaf area of the variety Phorma was more compared to Luit. A significant relationship between $N_2O$ emission and leaf area in the present study was (Table 4.21).

### 4.6.11. Root length (cm hill$^{-1}$)

Table 4.23 and 4.26 represents the root length (cm hill$^{-1}$) of the varieties Phorma and Luit, respectively. Root length increased up to 63 DAT and thereafter

declined in Phorma. Whereas, in Luit root length increased up to 56 DAT and then declined. In both the varieties there were variations in root length within the treatments.

### 4.6.12. Root volume (ml hill$^{-1}$)

Table 4.23 and 4.26 represents the root volume (ml hill$^{-1}$) of rice varieties Phorma and Luit, respectively. In both the varieties root volume gradually increased from 7 DAT up to 63 DAT and declined thereafter. Treatments were found to affect the root length in both the varieties.

### 4.6.13. Shoot dry weight (g hill$^{-1}$)

Table 4.24 and 4.27 represents the shoot dry weight of rice varieties Phorma and Luit, respectively. Shoot dry weight increased gradually from 7 DAT onwards and reached maximum at 77 and 70 DAT in Phorma and Luit, respectively. Shoot dry weight varied within treatments at different growth stages. However, the relationship between $N_2O$ emission and shoot dry weight in the present study is not significant (Table 4.21).

### 4.6.14. Root dry weight (g hill$^{-1}$)

Table 4.24 and 4.27 represents the root dry weight of the varieties Phorma and Luit, respectively. Root dry weights increased up to 56 DAT in both the varieties. The relationship between and $N_2O$ emission and root dry weights are found to be significant.

### . 4.6.15. Yield and yield attributing parameters

Data recorded on yield and yield attributing characteristics of rice varieties are presented in Table 4.28. Rice varieties at different levels of fertilizers recorded maximum yield in $T_7$ followed by $T_1$, $T_4$, $T_6$, $T_3$, $T_9$, $T_8$, $T_5$ and $T_2$. Compared to Phorma variety Luit had higher yield potential. Variety Luit also recorded higher thousand grain weights compared to Phorma. Higher grain sterility (%) was observed in treatment $T_2$ followed by $T_5$, $T_8$, $T_9$, $T_3$, $T_6$, $T_4$, $T_1$ and $T_7$ in both the varieties. variations in length of panicle within the treatments were not significant. Phorma recorded more number of panicle per unit area (square meter land area).

**Table: 4.21. Correlation of plant and soil parameters with nitrous oxide during fertilizer trial experiment at North Bank Plain Zone, Tezpur, Assam.**

| Varieties/Parameters | Correlation coefficient | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ | $T_9$ |
| **Phorma** | | | | | | | | | |
| Soil organic carbon (%) | 0.643* | 0.622* | 0.686* | 0.665* | 0.718* | 0.754** | 0.659* | 0.747** | 0.762** |
| Soil $NO_3^-$ - N (kg $ha^{-1}$) | 0.754** | 0.603* | 0.723* | 0.774** | 0.787** | 0.855** | 0.725* | 0.831** | 0.706* |
| Soil temperature (°C) | 0.382 | 0.425 | 0.499 | 0.438 | 0.447 | 0.493 | 0.388 | 0.441 | 0.469 |
| Soil pH | 0.115 | 0.292 | 0.144 | 0.123 | 0.126 | 0.032 | 0.072 | 0.019 | 0.201 |
| Tiller number ($hill^{-1}$) | 0.616* | 0.610* | 0.628* | 0.615* | 0.686* | 0.676* | 0.613* | 0.737** | 0.614* |
| Leaf area ($cm^2$ $hill^{-1}$) | 0.671* | 0.644* | 0.676* | 0.714* | 0.759** | 0.787** | 0.654* | 0.764** | 0.659* |
| Leaf number ($hill^{-1}$) | 0.585* | 0.581 | 0.619* | 0.630* | 0.709* | 0.735** | 0.608* | 0.718* | 0.636* |
| Plant height (cm) | 0.380 | 0.361 | 0.372 | 0.509 | 0.532 | 0.535 | 0.425 | 0.566 | 0.374 |
| Root length (cm $hill^{-1}$) | 0.534 | 0.499 | 0.530 | 0.619* | 0.664* | 0.682* | 0.547 | 0.683* | 0.533 |
| Root volume (ml $hill^{-1}$) | 0.411 | 0.387 | 0.391 | 0.550 | 0.580 | 0.592 | 0.450 | 0.588 | 0.441 |
| Shoot dry weight (g $hill^{-1}$) | 0.317 | 0.298 | 0.296 | 0.446 | 0.460 | 0.454 | 0.348 | 0.492 | 0.278 |
| Root dry weight (g $hill^{-1}$) | 0.624* | 0.604* | 0.607* | 0.694* | 0.735** | 0.745** | 0.640* | 0.760** | 0.615* |
| Water level (cm) | -0.276 | -0.225 | -0.276 | -0.427 | -0.437 | -0.448 | -0.380 | -0.486 | -0.311 |
| **Luit** | | | | | | | | | |
| Soil organic carbon (%) | 0.618* | 0.625* | 0.631* | 0.648* | 0.680* | 0.625* | 0.637* | 0.669* | 0.651* |
| Soil $NO_3^-$ - N (kg $ha^{-1}$) | 0.709* | 0.644* | 0.607* | 0.679* | 0.650* | 0.675* | 0.645* | 0.641* | 0.641* |
| Soil temperature (°C) | 0.383 | 0.421 | 0.406 | 0.260 | 0.501 | 0.233 | 0.351 | 0.264 | 0.244 |
| Soil pH | 0.487 | 0.147 | 0.434 | 0.544 | 0.358 | 0.407 | 0.379 | 0.307 | 0.237 |
| Tiller number ($hill^{-1}$) | 0.613* | 0.669* | 0.603* | 0.619* | 0.614* | 0.619* | 0.657* | 0.613* | 0.605* |
| Leaf area ($cm^2$ $hill^{-1}$) | 0.641* | 0.739** | 0.604* | 0.677* | 0.658* | 0.610* | 0.677* | 0.679* | 0.613* |
| Leaf number ($hill^{-1}$) | 0.466 | 0.529 | 0.403 | 0.504 | 0.461 | 0.348 | 0.470 | 0.499 | 0.436 |
| Plant height (cm) | 0.406 | 0.479 | 0.272 | 0.356 | 0.343 | 0.248 | 0.316 | 0.346 | 0.332 |
| Root length (cm $hill^{-1}$) | 0.555 | 0.631* | 0.447 | 0.514 | 0.506 | 0.440 | 0.522 | 0.526 | 0.494 |
| Root volume (ml $hill^{-1}$) | 0.395 | 0.474 | 0.280 | 0.351 | 0.359 | 0.227 | 0.307 | 0.362 | 0.277 |
| Shoot dry weight (g $hill^{-1}$) | 0.314 | 0.400 | 0.178 | 0.256 | 0.248 | 0 176 | 0.192 | 0.260 | 0.217 |
| Root dry weight (g $hill^{-1}$) | 0.607* | 0.723* | 0.605* | 0.638* | 0.621* | 0.602* | 0.635* | 0.654* | 0.603* |
| Water level (cm) | -0.328 | -0.310 | -0.128 | -0.140 | -0.148 | -0.130 | -0.169 | -0.176 | -0.168 |

* Correlation is significant at the 0.05 level of significance
** Correlation is significant at the 0.01 level of significance

**Table 4.22. Plant growth parameters (plant height, tiller number, leaf number) of rice variety Phorma during fertilizer trial experiment at North Bank Plain Zone, Tezpur, Assam.**

| Variety | Days after transplanting | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Phorma | 7 | 14 | 21 | 28 | 35 | 42 | 49 | 56 | 63 | 70 | 77 |
| **Plant height (cm)** | | | | | | | | | | | |
| $T_1$ | 26 63abc | 34 79a | 40 34b | 47 77cd | 62 46b | 72 77b | 85 15a | 98 03cd | 103 08a | 104 55a | 104 90a |
| $T_2$ | 27 53a | 34 85a | 40 09b | 47 20d | 62 91b | 72 50b | 84 99a | 97 60d | 102 32a | 104 33a | 104 67a |
| $T_3$ | 26 63abc | 34 10abc | 40 96ab | 48 40c | 63 66ab | 72 23b | 85 30a | 98 60abc | 103 05a | 104 67a | 105 07a |
| $T_4$ | 26 63abc | 34 62ab | 40 13b | 50 12b | 63 12b | 72 50b | 85 40a | 98 00cd | 102 95a | 104 49a | 104 83a |
| $T_5$ | 25 40c | 34 37ab | 40 33b | 50 10b | 62 58b | 72 23b | 85 00a | 97 67d | 102 84a | 104 50a | 104 80a |
| $T_6$ | 27 30ab | 33 82bc | 40 82b | 50 10b | 63 55ab | 72 80b | 85 13a | 98 13bcd | 102 74a | 104 47a | 104 77a |
| $T_7$ | 26 27abc | 34 33ab | 40 99ab | 50 77ab | 64 87a | 72 97ab | 85 63a | 98 43abcd | 102 94a | 104 47a | 104 83a |
| $T_8$ | 25 90bc | 34 84a | 40 57b | 50 63ab | 64 60a | 72 77b | 84 97a | 98 87ab | 102 43a | 104 57a | 104 90a |
| $T_9$ | 25 63c | 33 31c | 42 75a | 51 13a | 64 80a | 73 63a | 85 20a | 99 00a | 102 95a | 104 33a | 104 73a |
| CD (5%) | 1 31 | 0 79 | 1 77 | 0 63 | 1 21 | 0 72 | 0 75 | 0 76 | 0 91 | 0 64 | 0 68 |
| **Tiller number (hill$^{-1}$)** | | | | | | | | | | | |
| $T_1$ | 3 20a | 5 00a | 6 63a | 10 00a | 14 50a | 15 00ab | 15 43b | 15 90a | 15 40ab | 15 17ab | 14 00d |
| $T_2$ | 3 50a | 4 00b | 6 00b | 9 00b | 13 03c | 14 00b | 16 50a | 16 03a | 15 80a | 15 50ab | 14 00d |
| $T_3$ | *3 20a* | *4 87a* | *6 73a* | *8 00c* | *13 50b* | *14 97ab* | *15 57b* | *15 80a* | *15 00b* | *14 80b* | *14 00d* |
| $T_4$ | 3 20a | 5 00a | 6 97a | 10 17a | 13 50b | 15 17a | 15 40b | 15 90a | 15 73a | 15 47ab | 14 87ab |
| $T_5$ | 3 43a | 4 97a | 6 63a | 9 63a | 12 97c | 14 63ab | 15 40b | 16 00a | 15 80a | 15 30ab | 14 77ab |
| $T_6$ | 3 30a | 5 30a | 6 97a | 9 97a | 13 30bc | 15 07a | 15 17b | 16 30a | 15 80a | 15 67a | 15 37a |
| $T_7$ | 3 13a | 4 90a | 6 60a | 9 97a | 14 50a | 15 03ab | 15 43b | 15 87a | 15 77a | 15 40ab | 15 30a |
| $T_8$ | 3 00a | 4 97a | 6 60a | 10 20a | 14 27a | 15 20a | 15 30b | 15 63a | 15 57a | 15 00ab | 14 10cd |
| $T_9$ | 3 13a | 5 03a | 6 50ab | 10 00a | 14 13a | 14 93ab | 15 53b | 15 67a | 15 40ab | 15 07ab | 14 63bc |
| CD (5%) | 0 51 | 0 51 | 0 52 | 0 55 | 0 40 | 0 93 | 0 64 | 0 69 | 0 44 | 0 66 | 0 57 |
| **Leaf number (hill$^{-1}$)** | | | | | | | | | | | |
| $T_1$ | 13 53a | 27 17a | 39 22cd | 43 63cd | 58 53c | 66 40b | 69 20bc | 71 87cd | 73 93abc | 62 30b | 44 97c |
| $T_2$ | *13 77a* | *26 63ab* | *38 55e* | *42 97d* | *58 30c* | *67 67ab* | *68 73b* | *71 30d* | *74 40a* | *62 83ab* | *44 87c* |
| $T_3$ | 12 97ab | 26 77ab | 39 78c | 44 30c | 58 83bc | 67 63ab | 69 63a | 72 07abcd | 74 17ab | 62 63b | 45 30bc |
| $T_4$ | 12 40b | 26 97ab | 41 66c | 46 53b | 60 73a | 67 83ab | 70 00a | 73 00ab | 73 83abc | 62 20b | 45 43bc |
| $T_5$ | 13 40a | 26 73ab | 41 66c | 46 20b | 59 20bc | 68 10a | 69 73a | 71 63d | 72 93bc | 63 40ab | 46 07a |
| $T_6$ | 12 40b | 26 63ab | 42 11bc | 46 73b | 59 63abc | 67 63ab | 70 00a | 73 07a | 73 30abc | 62 40b | 45 40bc |
| $T_7$ | 13 20ab | 26 97ab | 42 89b | 50 33a | 60 77a | 68 63a | 70 07a | 71 97bcd | 72 83c | 64 67a | 45 30bc |
| $T_8$ | 13 07ab | 26 87ab | 41 77c | 50 07a | 60 20ab | 67 87ab | 69 87a | 72 73abc | 73 07bc | 62 87ab | 45 73ab |
| $T_9$ | 12 97ab | 26 22b | 44 44a | 50 53a | 60 73a | 68 87a | 70 07a | 71 20d | 72 97bc | 64 63a | 45 30bc |
| CD (5%) | 0 73 | 0 72 | 0 82 | 0 96 | 1 30 | 1 42 | 0 83 | 0 99 | 1 14 | 1 78 | 0 58 |

**Treatments.** $T_1$: N, $P_2O_5$, $K_2O$ @ 40: 20: 20 kg ha$^{-1}$ as Urea, SSP, MOP,$T_2$: N, $P_2O_5$, $K_2O$ @ 35.18.18 kg ha$^{-1}$ as Urea, SSP, MOP, $T_3$: N, $P_2O_5$, $K_2O$ @ 45 22·22 kg ha$^{-1}$ as Urea, SSP, MOP, $T_4$: N, $P_2O_5$, $K_2O$ @ 40:20.20 kg ha$^{-1}$ as Urea, DAP, MOP, $T_5$: N, $P_2O_5$, $K_2O$ @ 35.18:18 kg ha$^{-1}$ as Urea, DAP, MOP, $T_6$: N, $P_2O_5$, $K_2O$ @ 45:22·22 kg ha$^{-1}$ as Urea, DAP, MOP, $T_7$: N, $P_2O_5$, $K_2O$ @ 40·20·20 kg ha$^{-1}$ as Urea, SSP, MOP + FYM, $T_8$: N, $P_2O_5$, $K_2O$ @ 35 18.18 kg ha$^{-1}$ as Urea, SSP, MOP + FYM, $T_9$: N, $P_2O_5$, $K_2O$ @ 45:22.22 kg ha$^{-1}$ as Urea, SSP, MOP + FYM

**Table 4.23. Plant growth parameters (leaf area, root length, root volume) of rice variety Phorma during fertilizer trial experiment at North Bank Plain Zone, Tezpur, Assam.**

| Variety | Days after transplanting | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Phorma | 7 | 14 | 21 | 28 | 35 | 42 | 49 | 56 | 63 | 70 | 77 |
| Leaf area ($cm^2$ $hill^{-1}$) | | | | | | | | | | | |
| $T_1$ | 34 40a | 89 04a | 143 85d | 313 22bc | 643 27c | 833 34c | 920 64c | 941 19cd | 815 22e | 678 20bc | 647 25c |
| $T_2$ | 33 69a | 89 35a | 144 06d | 311 98c | 643 92c | 828 52d | 919 45c | 939 97d | 811 47e | 663 14d | 652 11bc |
| $T_3$ | 33 23a | 89 29a | 145 13d | 315 24abc | 644 16c | 837 28b | 922 60c | 940 82cd | 834 26d | 675 86c | 631 11d |
| $T_4$ | 33 16a | 89 35a | 149 23c | 317 46ab | 649 21bc | 844 86a | 930 44ab | 943 54bc | 850 14c | 681 35bc | 657 27bc |
| $T_5$ | 33 91a | 89 65a | 148 96c | 318 27a | 649 56abc | 838 56b | 927 80b | 942 61bcd | 852 35bc | 679 47bc | 655 64bc |
| $T_6$ | 33 91a | 89 21a | 149 98c | 317 24ab | 650 29abc | 843 94a | 931 35ab | 942 56bcd | 861 17b | 683 24b | 658 99b |
| $T_7$ | 32 89a | 89 43a | 153 00ab | 319 65a | 656 90ab | 846 87a | 933 89a | 943 56bc | 934 82a | 694 51a | 682 36a |
| $T_8$ | 34 00a | 89 36a | 152 55b | 319 34a | 654 22ab | 843 60a | 931 87ab | 944 80ab | 927 91a | 692 53a | 682 26a |
| $T_9$ | 32 84a | 88 27a | 154 38a | 319 65a | 657 65a | 847 71a | 934 48a | 946 84a | 935 57a | 699 18a | 682 92a |
| CD (5%) | 3 87 | 3 12 | 1 74 | 4 57 | 7 47 | 3 86 | 4 15 | 2 50 | 9 94 | 6 70 | 10 00 |
| Root length (cm $hill^{-1}$) | | | | | | | | | | | |
| $T_1$ | 141 60a | 186 36a | 249 45f | 530 20cd | 643 27c | 1122 26d | 1213 89f | 1273 27ef | 1281 62bc | 1231 34c | 1026 34c |
| $T_2$ | 141 85a | 186 35a | 247 35f | 528 93d | 643 92c | 1118 10e | 1209 92f | 1271 74f | 1277 91cd | 1232 16c | 1026 98c |
| $T_3$ | 141 55a | 186 68a | 254 37e | 530 30cd | 644 16c | 1122 69d | 1218 50e | 1275 18def | 1270 81d | 1234 53c | 1025 59c |
| $T_4$ | 141 79a | 186 23a | 259 73cd | 533 28bcd | 649 21bc | 1124 14cd | 1229 09cd | 1282 19bcd | 1283 62bc | 1256 29b | 1026 48c |
| $T_5$ | 142 18a | 185 91a | 257 96d | 533 60bcd | 649 56bc | 1123 35cd | 1227 87d | 1281 50cde | 1283 94bc | 1255 94b | 1028 00c |
| $T_6$ | 142 87a | 186 29a | 261 58c | 534 89abc | 650 29abc | 1124 56cd | 1231 47bcd | 1284 52bc | 1289 19b | 1261 32b | 1032 06bc |
| $T_7$ | 142 18a | 185 54a | 274 97b | 538 38ab | 656 90ab | 1128 50ab | 1235 55ab | 1293 50a | 1305 07a | 1285 60a | 1041 66a |
| $T_8$ | 141 88a | 185 78a | 275 86b | 539 25a | 654 22ab | 1126 17bc | 1233 14abc | 1290 63ab | 1300 91a | 1284 74a | 1037 47ab |
| $T_9$ | 141 46a | 186 59a | 279 54a | 538 27ab | 657 65a | 1130 19a | 1237 20a | 1293 92a | 1305 85a | 1287 25a | 1043 54a |
| CD (5%) | 2 95 | 2 81 | 3 20 | 4 97 | 7 15 | 2 95 | 4 30 | 8 09 | 8 29 | 6 30 | 6 84 |
| Root volume (ml $hill^{-1}$) | | | | | | | | | | | |
| $T_1$ | 0 17a | 0 40a | 0 53c | 0 87d | 1 61d | 2 87d | 3 50b | 4 33c | 4 47b | 4 17cd | 3 90a |
| $T_2$ | 0 20a | 0 43a | 0 60abc | 0 90cd | 1 61d | 2 50e | 3 47b | 4 50bc | 4 57ab | 4 10d | 3 93a |
| $T_3$ | 0 17a | 0 47a | 0 57bc | 0 93bcd | 1 62d | 3 13cd | 3 53b | 4 33c | 4 60ab | 4 20cd | 3 97a |
| $T_4$ | 0 17a | 0 47a | 0 60abc | 0 97abc | 1 63cd | 3 40bc | 3 87ab | 4 67abc | 4 70ab | 4 30bcd | 4 10a |
| $T_5$ | 0 13a | 0 43a | 0 60abc | 0 97abc | 1 62d | 3 43abc | 3 90ab | 4 47bc | 4 60ab | 4 50abc | 4 17a |
| $T_6$ | 0 17a | 0 50a | 0 63abc | 1 01ab | 1 63bcd | 3 53ab | 3 90ab | 4 60abc | 4 73ab | 4 20cd | 4 03a |
| $T_7$ | 0 17a | 0 43a | 0 67ab | 1 03a | 1 66ab | 3 70ab | 4 20a | 4 87ab | 4 87ab | 4 67ab | 4 43a |
| $T_8$ | 0 13a | 0 50a | 0 67ab | 1 03a | 1 65abc | 3 63ab | 4 00ab | 4 73abc | 4 87ab | 4 50abc | 4 30a |
| $T_9$ | 0 13a | 0 47a | 0 70a | 1 04a | 1 67a | 3 73a | 4 27a | 4 93a | 5 00c | 4 80a | 4 23a |
| CD (5%) | 0 11 | 0 10 | 0 11 | 0 09 | 0 03 | 0 30 | 0 54 | 0 38 | 0 39 | 0 35 | 0 47 |

**Table 4.24. Plant growth parameters (shoot dry weight, root dry weight) of rice variety Phorma during fertilizer trial experiment at North Bank Plain Zone, Tezpur, Assam.**

| Variety | Days after transplanting | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Phorma | 7 | 14 | 21 | 28 | 35 | 42 | 49 | 56 | 63 | 70 | 77 |
| Shoot dry weight (g hill$^{-1}$) | | | | | | | | | | | |
| $T_1$ | 0 27a | 1 30a | 1 53f | 7 89bc | 10 21d | 14 91e | 22 07e | 28 14a | 31 84d | 32 87f | 33 17e |
| $T_2$ | 0 28a | 1 29ab | 1 54ef | 7 82c | 10 23d | 14 87e | 21 98e | 27 98a | 31 76d | 32 80g | 33 12e |
| $T_3$ | 0 27a | 1 30a | 1 56def | 7 91bc | 10 24d | 14 95de | 22 14de | 28 62a | 31 85d | 32 96e | 33 25d |
| $T_4$ | 0 26a | 1 28abc | 1 58cde | 7 91bc | 10 38bc | 15 06bc | 22 25cd | 28 03a | 32 37bc | 33 58cd | 34 83c |
| $T_5$ | 0 26a | 1 30a | 1 55ef | 7 93bc | 10 35c | 15 01cd | 22 15cde | 28 73a | 32 30c | 33 54d | 34 81c |
| $T_6$ | 0 25a | 1 24d | 1 59cd | 7 95b | 10 38bc | 15 08bc | 22 32c | 28 02a | 32 48b | 33 61c | 34 93b |
| $T_7$ | 0 27a | 1 23d | 1 65ab | 8 07a | 10 48a | 15 20a | 22 68a | 29 12a | 32 99a | 34 45ab | 35 15a |
| $T_8$ | 0 26a | 1 25bcd | 1 62bc | 8 07a | 10 45ab | 15 16ab | 22 50b | 28 14a | 32 96a | 34 44b | 35 15a |
| $T_9$ | 0 27a | 1 26bcd | 1 67a | 8 07a | 10 49a | 15 22a | 22 78a | 29 03a | 33 01a | 34 50a | 35 15a |
| CD (5%) | 0 03 | 0 04 | 0 04 | 0 10 | 0 07 | 0 10 | 0 17 | 1 04 | 0 13 | 0 05 | 0 07 |
| Root dry weight (g hill$^{-1}$) | | | | | | | | | | | |
| $T_1$ | 0 22a | 0 36a | 0 49a | 1 07c | 3 93a | 4 62a | 5 01b | 5 23b | 5 11a | 4 95b | 4 34a |
| $T_2$ | 0 22a | 0 33a | 0 50a | 2 34a | 4 00a | 4 50a | 5 26a | 5 34a | 5 13a | 5 02a | 4 16b |
| $T_3$ | 0 22a | 0 36a | 0 51a | 2 02b | 3 99a | 4 62a | 5 02b | 5 22b | 5 13a | 4 96b | 4 33a |
| $T_4$ | 0 22a | 0 36a | 0 50a | 1 02c | 4 00a | 4 50a | 5 00b | 5 25b | 5 12a | 4 95b | 4 32a |
| $T_5$ | 0 22a | 0 36a | 0 51a | 1 00c | 4 00a | 4 51a | 5 01b | 5 24b | 5 11a | 4 95b | 4 32a |
| $T_6$ | 0 22a | 0 36a | 0 51a | 1 00c | 4 00a | 4 51a | 5 01b | 5 23b | 5 12a | 5 95b | 4 33a |
| $T_7$ | 0 22a | 0 37a | 0 51a | 1 01c | 4 04a | 4 51a | 5 03b | 5 23b | 5 11a | 4 95b | 4 35a |
| $T_8$ | 0 22a | 0 36a | 0 51a | 1 01c | 4 02a | 4 50a | 5 01b | 5 23b | 5 13a | 4 94b | 4 34a |
| $T_9$ | 0 22a | 0 33a | 0 50a | 1 00c | 4 02a | 4 50a | 5 01b | 5 24b | 5 10a | 4 94b | 4 36a |
| CD (5%) | 0 03 | 0 05 | 0 06 | 0 31 | 0 11 | 0 50 | 0 13 | 0 08 | 0 09 | 0 10 | 0 12 |

**Table 4.25. Plant growth parameters (plant height, tiller number, leaf number) of rice variety Luit during fertilizer trial experiment at North Bank Plain Zone, Tezpur, Assam.**

| Variety | Days after transplanting | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Luit | 7 | 14 | 21 | 28 | 35 | 42 | 49 | 56 | 63 | 70 | 77 |
| **Plant height (cm)** | | | | | | | | | | | |
| $T_1$ | 19 60a | 26 25a | 33 62cd | 40 87cd | 52 19bcd | 62 30a | 74 57a | 79 17bc | 82 10abc | 82 93a | 83 33bc |
| $T_2$ | 19 07a | 25 87a | 33 53cd | 40 13d | 51 19d | 62 27a | 75 03a | 78 87bc | 81 70c | 82 67a | 83 07b |
| $T_3$ | 19 27a | 26 47a | 33 93bcd | 40 50d | 51 75cd | 62 40a | 74 77a | 79 50bc | 81 77bc | 82 87a | 83 30bc |
| $T_4$ | 19 27a | 25 67a | 34 22bc | 41 70bc | 52 23bcd | 62 33a | 74 87a | 79 33bc | 82 43ab | 83 03a | 83 40bc |
| $T_5$ | 19 73a | 25 98a | 34 02bc | 41 43bc | 51 32d | 62 63a | 75 13a | 79 67bc | 82 05abc | 82 67a | 83 30bc |
| $T_6$ | 19 87a | 25 57a | 34 27bc | 43 77a | 51 90cd | 62 73a | 74 53a | 79 77bc | 82 56a | 83 23a | 83 57bc |
| $T_7$ | 19 37a | 26 24a | 34 63ab | 43 07a | 53 77a | 63 20a | 74 40a | 79 43bc | 82 63a | 83 50a | 83 53bc |
| $T_8$ | 19 77a | 25 57a | 34 99a | 42 97a | 53 10abc | 62 43a | 74 74a | 79 98a | 82 51a | 83 17a | 83 77bc |
| $T_9$ | 19 20a | 25 83a | 33 20d | 42 03b | 53 40ab | 63 03a | 74 67a | 80 03a | 82 77a | 83 40a | 83 80a |
| CD (5%) | 1 08 | 0 88 | 0 68 | 0 80 | 1 23 | 1 01 | 0 72 | 0 83 | 0 65 | 0 75 | 0 64 |
| **Tiller number ($hill^{-1}$)** | | | | | | | | | | | |
| $T_1$ | 3 30bc | 4 00c | 5 00e | 8 00ab | 11 50bc | 13 97b | 14 30bc | 14 10a | 12 34c | 11 20cde | 11 10ab |
| $T_2$ | 3 40abc | 4 87a | 6 20cd | 8 10ab | 11 00cd | 14 30ab | 14 73ab | 14 50a | 13 41b | 11 63bcd | 11 30ab |
| $T_3$ | 4 00a | 4 73a | 6 73ab | 7 63b | 10 97cd | 13 00bc | 15 00a | 12 50d | 12 30c | 12 10ab | 11 00bc |
| $T_4$ | 3 30bc | 4 73a | 7 00a | 8 30ab | 12 00b | 13 73b | 14 00c | 13 63b | 12 00c | 11 63bcd | 11 30ab |
| $T_5$ | 3 20bc | 4 60ab | 5 87d | 7 97ab | 10 53d | 13 97b | 14 90a | 14 10a | 13 06b | 11 17de | 10 97bc |
| $T_6$ | 3 40abc | 4 10c | 7 00a | 8 30ab | 12 00b | 13 00c | 14 67ab | 12 00e | 11 00 | 10 90e | 10 47c |
| $T_7$ | 2 77c | 4 30bc | 6 40bc | 8 43a | 13 00 | 14 63a | 14 73ab | 13 00c | 12 00c | 11 83bc | 11 63a |
| $T_8$ | 3 53ab | 4 30bc | 6 20cd | 8 10ab | 12 00a | 13 00c | 14 77ab | 14 20a | 13 88a | 12 00ab | 11 40ab |
| $T_9$ | 3 30bc | 4 10c | 6 83ab | 8 53a | 12 00b | 13 00c | 14 87ab | 14 40a | 13 00b | 12 50a | 11 00bc |
| CD (5%) | 0 59 | 0 39 | 0 46 | 0 67 | 0 52b | 0 55 | 0 52 | 0 43 | 0 42 | 0 59 | 0 55 |
| **Leaf number ($hill^{-1}$)** | | | | | | | | | | | |
| $T_1$ | 10 63a | 21 88b | 37 00d | 40 17d | 43 63cd | 44 50c | 47 53d | 51 97a | 53 07ab | 42 10bc | 31 07c |
| $T_2$ | 10 47a | 22 11b | 36 00e | 41 07cd | 43 43d | 45 07c | 48 10cd | 50 53bcd | 53 30ab | 41 20c | 31 53c |
| $T_3$ | 10 73a | 21 77bc | 37 67cd | 40 77cd | 44 40abcd | 46 53b | 48 43bcd | 51 50ab | 53 07ab | 42 63ab | 31 20c |
| $T_4$ | 10 87a | 22 78b | 38 78ab | 41 27bc | 44 83abc | 46 97b | 49 30ab | 50 67bcd | 52 07bc | 43 20ab | 31 40c |
| $T_5$ | 10 27a | 22 22b | 38 89ab | 40 50cd | 44 40abcd | 46 40b | 48 87bc | 50 87abc | 52 73abc | 42 63ab | 31 07c |
| $T_6$ | 10 73a | 23 66b | 38 09bc | 42 10ab | 44 20bcd | 46 87b | 47 63d | 50 63bcd | 53 50a | 43 63a | 31 40c |
| $T_7$ | 10 73a | 22 11b | 39 44a | 42 40a | 45 43ab | 46 53b | 49 07abc | 50 10cd | 52 43abc | 42 30b | 34 30b |
| $T_8$ | 10 63a | 22 55bc | 38 22bc | 42 43a | 45 30ab | 47 07b | 50 10a | 50 17cd | 51 77c | 43 07ab | 31 30c |
| $T_9$ | 11 07a | 21 67b | 39 78a | 42 70a | 45 63a | 47 87a | 49 17abc | 49 53d | 51 73c | 43 43a | 41 63a |
| CD (5%) | 1 07 | 1 10 | 0 96 | 0 93 | 1 23 | 0 73 | 1 07 | 1 17 | 1 12 | 1 00 | 1 60 |

**Table 4.26. Plant growth parameters (leaf area, root length, root volume) of rice variety Luit during fertilizer trial experiment at North Bank Plain Zone, Tezpur, Assam.**

| Variety | Days after transplanting | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Luit | 7 | 14 | 21 | 28 | 35 | 42 | 49 | 56 | 63 | 70 | 77 |
| Leaf area ($cm^2$ $hill^{-1}$) | | | | | | | | | | | |
| $T_1$ | 23 45c | 78 09a | 129 45c | 220 66b | 530 13d | 633 16c | 680 38f | 696 74e | 544 00e | 382 56e | 364 85e |
| $T_2$ | 23 94c | 65 99b | 128 93c | 220 19b | 531 83d | 592 58e | 675 18g | 696 26e | 534 80e | 371 94f | 363 16e |
| $T_3$ | 29 72b | 79 30a | 130 54c | 220 84ba | 533 00d | 582 49f | 705 65b | 705 79d | 586 74c | 493 35b | 368 20d |
| $T_4$ | 22 83c | 79 13a | 134 62b | 229 94a | 540 89c | 644 14b | 688 23e | 705 47d | 618 26b | 407 94d | 379 75c |
| $T_5$ | 23 86c | 79 34a | 135 21b | 229 62a | 540 41c | 641 92b | 686 35 | 704 93d | 593 27c | 403 34d | 379 49c |
| $T_6$ | 33 68a | 65 99b | 135 39b | 231 23a | 539 99c | 606 95d | 709 39a | 711 06c | 571 63d | 511 91a | 322 25f |
| $T_7$ | 24 29c | 79 12a | 139 94a | 232 69a | 559 89ab | 651 82a | 696 44c | 714 65ab | 630 80a | 417 42c | 395 94b |
| $T_8$ | 24 23c | 78 25a | 139 37a | 231 68a | 555 28b | 649 27a | 691 94d | 713 01bc | 626 33ab | 417 44c | 393 84b |
| $T_9$ | 23 36c | 77 03a | 139 82a | 232 28a | 562 85a | 652 94a | 697 39c | 717 56a | 629 03ab | 418 58c | 408 80a |
| CD (5%) | 3 29 | 2 99 | 2 33 | 3 93 | 6 30 | 4 89 | 3 52 | 3 14 | 10 73 | 6 92 | 3 01 |
| Root length (cm $hill^{-1}$) | | | | | | | | | | | |
| $T_1$ | 139 36a | 179 17a | 225 64e | 412 52bc | 850 77cd | 932 26cd | 1023 86d | 1061 27c | 1050 70e | 1042 98ab | 929 64bc |
| $T_2$ | 140 23a | 180 03a | 219 32f | 408 93c | 847 87d | 931 25d | 1021 80d | 1060 15c | 1050 40e | 1030 28bc | 927 85bc |
| $T_3$ | 140 16a | 180 29a | 227 64de | 410 57bc | 851 21cd | 933 90bcd | 1028 59c | 1065 11c | 1057 87de | 1044 83ab | 926 59c |
| $T_4$ | 136 62a | 178 87a | 237 25c | 413 30bc | 854 28bc | 936 50bc | 1032 30ab | 1077 58b | 1071 24c | 1038 46abc | 937 53b |
| $T_5$ | 139 61a | 180 79a | 230 51d | 412 80bc | 852 25bcd | 935 23bcd | 1029 71bc | 1068 26c | 1062 14d | 1030 58bc | 935 95bc |
| $T_6$ | 139 68a | 177 87a | 238 68c | 416 31ab | 854 94bc | 936 91bc | 1032 56ab | 1088 11a | 1072 87bc | 1052 28a | 935 60bc |
| $T_7$ | 139 35a | 176 23a | 246 00ab | 420 23a | 860 39a | 938 91ab | 1034 60a | 1085 15a | 1079 55ab | 1044 92ab | 950 00a |
| $T_8$ | 139 31a | 180 55a | 243 24b | 420 23a | 856 62ab | 938 55ab | 1033 88a | 1091 10a | 1084 95a | 1026 18c | 952 99a |
| $T_9$ | 139 49a | 179 18a | 248 68a | 419 6 2a | 859 94a | 942 49a | 1035 11a | 1090 92a | 1081 61a | 1032 39bc | 950 77a |
| CD (5%) | 3 76 | 4 66 | 4 16 | 5 59 | 4 26 | 4 72 | 3 25 | 7 53 | 7 13 | 13 09 | 9 68 |
| Root volume (ml $hill^{-1}$) | | | | | | | | | | | |
| $T_1$ | 0 17a | 0 33a | 0 53b | 0 60c | 1 40a | 2 33d | 3 20cd | 3 77cd | 3 83cd | 3 23e | 2 87c |
| $T_2$ | 0 13a | 0 40a | 0 50b | 0 63bc | 1 20a | 2 20d | 3 01d | 3 60d | 3 63d | 3 20e | 2 93c |
| $T_3$ | 0 17a | 0 30a | 0 50b | 0 70bc | 1 40a | 2 43cd | 3 27c | 3 93cd | 4 00bc | 3 37de | 2 93c |
| $T_4$ | 0 13a | 0 33a | 0 60ab | 0 77abc | 1 20a | 2 70abc | 3 37bc | 4 47ab | 4 53a | 3 63cd | 3 23bc |
| $T_5$ | 0 17a | 0 33a | 0 60ab | 0 80abc | 1 40a | 2 47bcd | 3 37bc | 4 13bc | 4 20b | 3 50cde | 3 00c |
| $T_6$ | 0 13a | 0 40a | 0 63ab | 0 80abc | 1 40a | 2 80ab | 3 43abc | 4 47ab | 4 67a | 3 70bcd | 3 20bc |
| $T_7$ | 0 13a | 0 33a | 0 70a | 0 80abc | 1 67a | 3 00a | 3 57ab | 4 60a | 4 67a | 4 00ab | 3 63ab |
| $T_8$ | 0 13a | 0 30a | 0 70a | 0 83ab | 1 37a | 2 93a | 3 63a | 4 60a | 4 70a | 3 80bc | 3 37abc |
| $T_9$ | 0 10a | 0 40a | 0 70a | 0 97a | 1 60a | 3 00a | 3 63a | 4 60a | 4 63a | 4 20a | 3 80a |
| CD (5%) | 0 09 | 0 10 | 0 12 | 0 20 | 0 54 | 0 34 | 0 22 | 0 39 | 0 31 | 0 34 | 0 47 |

**Table 4.27. Plant growth parameters (shoot dry weight, root dry weight) of rice variety Luit during fertilizer trial experiment at North Bank Plain Zone, Tezpur, Assam.**

| Variety | Days after transplanting | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Luit | 7 | 14 | 21 | 28 | 35 | 42 | 49 | 56 | 63 | 70 | 77 |
| **Shoot dry weight (g hill$^{-1}$)** | | | | | | | | | | | |
| $T_1$ | 0 20a | 0 97a | 1 29d | 4 60cd | 7 11b | 12 19b | 22 07e | 23 79c | 28 46c | 29 54d | 28 41c |
| $T_2$ | 0 19a | 0 96ab | 1 26e | 4 58d | 7 11b | 12 18b | 21 98e | 24 00c | 28 37c | 29 49d | 27 39e |
| $T_3$ | 0 20a | 0 95ab | 1 30d | 4 61cd | 7 13b | 12 20b | 22 14d | 24 22bc | 28 46c | 29 64c | 27 40e |
| $T_4$ | 0 20a | 0 93abc | 1 35c | 4 69c | 7 14b | 12 25b | 22 25cd | 25 29ab | 28 75b | 29 88b | 28 76b |
| $T_5$ | 0 20a | 0 95ab | 1 35c | 4 68c | 7 14b | 12 22b | 22 15cde | 24 99abc | 28 74b | 29 86b | 27 51e |
| $T_6$ | 0 20a | 0 95ab | 1 36bc | 4 69c | 7 14b | 12 26b | 22 32c | 24 92abc | 28 80b | 29 88b | 27 84d |
| $T_7$ | 0 20a | 0 94abc | 1 39ab | 4 99b | 7 22a | 12 40a | 22 68a | 26 09a | 29 28a | 30 47a | 29 19a |
| $T_8$ | 0 20a | 0 95ab | 1 39a | 4 91b | 7 20a | 12 38a | 22 50b | 25 80a | 29 14a | 30 43a | 28 10d |
| $T_9$ | 0 20a | 0 91c | 1 40a | 5 15a | 7 23a | 12 42a | 22 78a | 26 00a | 29 29a | 30 48a | 29 25a |
| CD (5%) | 0 02 | 0 03 | 0 03 | 0 10 | 0 06 | 0 08 | 0 17 | 1 15 | 0 14 | 0 08 | 0 27 |
| **Root dry weight (g hill$^{-1}$)** | | | | | | | | | | | |
| $T_1$ | 0 16a | 0 30b | 0 87bc | 2 83a | 3 98b | 4 23b | 5 43b | 5 53b | 4 93b | 4 71a | 3 90a |
| $T_2$ | 0 16a | 0 20c | 0 93bc | 1 92b | 3 88b | 4 23b | 5 77a | 5 80a | 4 82bc | 4 41bc | 3 51b |
| $T_3$ | 0 17a | 0 20c | 1 37a | 1 73b | 4 53a | 4 83a | 5 77a | 5 83a | 4 72bc | 3 97c | 3 12c |
| $T_4$ | 0 15a | 0 20c | 1 03b | 1 92b | 3 87b | 4 50b | 5 80a | 5 93a | 5 29a | 4 33c | 3 51b |
| $T_5$ | 0 07b | 0 19c | 0 80bc | 1 87b | 3 83b | 4 24b | 5 73ab | 5 84a | 4 74bc | 4 37bc | 3 46b |
| $T_6$ | 0 16a | 0 18c | 1 30a | 1 70b | 4 62a | 4 86a | 5 74a | 5 84a | 4 58c | 4 14d | 3 23c |
| $T_7$ | 0 16a | 0 20c | 0 70c | 1 90b | 3 86b | 4 27b | 5 76a | 5 87a | 4 78bc | 4 39bc | 3 48b |
| $T_8$ | 0 17a | 0 40a | 0 78bc | 1 94b | 3 86b | 4 30b | 5 50ab | 5 54b | 4 67c | 4 50b | 3 52b |
| $T_9$ | 0 15a | 0 19c | 0 90bc | 1 91b | 3 87b | 4 29b | 5 78a | 5 88a | 4 80bc | 4 41bc | 3 50b |
| CD (5%) | 0 05 | 0 04 | 0 26 | 0 23 | 0 22 | 0 30 | 0 28 | 0 25 | 0 22 | 0 15 | 0 19 |

**Table 4.28. Yield and yield attributing parameters of rice varieties and seasonal integrated nitrous oxide emission flux ($E_{sif}$) during fertilizer trial experiment at North Bank Plain Zone, Tezpur, Assam.**

| Rice varieties/ Parameters | Panicle square meter$^{-1}$ | Panicle length (cm) | Sterility (%) | Thousand grain weight (g) | Yield (q ha $^{-1}$) | $E_{sif}$ (mg $N_2O$-N $m^{-2}$) |
|---|---|---|---|---|---|---|
| **Phorma** | | | | | | |
| $T_1$ | 253.00ab | 22.70a | 8.12dab | 19.80a | 26.10ab | 175.56 h |
| $T_2$ | 251.67ab | 22.97a | 11.57a | 19.15c | 25.29 e | 169.34 i |
| $T_3$ | 252.00ab | 22.93a | 10.85ab | 19.84a | 25.77abcd | 179.81g |
| $T_4$ | 253.33ab | 22.37a | 9.76c | 19.95a | 26.07ab | 190.28 f |
| $T_5$ | 250.00b | 22.43a | 11.39ab | 19.26c | 25.50 de | 192.86 e |
| $T_6$ | 252.67ab | 22.47a | 10.65ab | 19.80a | 25.97abc | 196.84 d |
| $T_7$ | 254.33ab | 22.13a | 8.06d | 19.71a | 26.17 a | 212.29 b |
| $T_8$ | 255.67a | 22.63a | 11.19ab | 19.48b | 25.57 cde | 205.46 c |
| $T_9$ | 252.33ab | 22.63a | 11.00ab | 19.79a | 25.70bcde | 224.05 a |
| **Luit** | | | | | | |
| $T_1$ | 236.00ab | 21.77a | 4.63g | 23.92a | 29.03 a | 118.94 g |
| $T_2$ | 232.00c | 20.97a | 7.30a | 23.12b | 28.17 c | 117.54 g |
| $T_3$ | 233.67abc | 20.80a | 5.70e | 23.73a | 28.83 abc | 121.85 f |
| $T_4$ | 235.00abc | 20.90a | 4.70g | 23.74a | 28.97 ab | 162.79 e |
| $T_5$ | 232.33bc | 20.90a | 6.80b | 23.18b | 28.27 bc | 161.61 e |
| $T_6$ | 234.33abc | 21.43a | 5.00f | 23.87a | 28.93 ab | 168.67 d |
| $T_7$ | 236.33a | 21.57a | 4.54g | 23.89a | 29.10 a | 179.98 b |
| $T_8$ | 232.67abc | 21.20a | 6.50c | 23.64a | 28.37 abc | 177.74 c |
| $T_9$ | 233.00abc | 20.67a | 6.27d | 23.67a | 28.77 abc | 182.16 a |

# Chapter 5
# DISCUSSION

# 5. DISCUSSION

**Seasonal and temporal variations in $N_2O$ emission from rice and wheat ecosystems**

In the present investigation variations in $N_2O$ emissions were studied from rice and wheat growing ecosystems. Ecosystems of rice mentioned above were autumn (May-July, 2006), monsoon (July-November, 2006) and summer rice (February-June, 2007) ecosystem and in wheat it was rain-fed (December, 2006-April, 2007) and irrigated ecosystem (December, 2007-April, 2008). Further, impact of different types and doses of fertilizer on $N_2O$ emission from autumn rice ecosystem (May-August, 2008) was also investigated. Temporal variations in $N_2O$ emission was observed in all the varieties with emission peaks at various growth stages, irrespective of ecosystems. Findings are elaborately presented in the results chapter.

In autumn (*Ahu*) rice ecosystem $N_2O$ emission in all the tested varieties were initially low up to 28 DAT (days after transplanting) with small emission peaks at 7 DAT. The observed minor emission peaks at 7 DAT coincides with the basal application of nitrogenous fertilizer at the time of transplanting along with the mineralized soil organic nitrogen from the stubble of previous season's crop a mechanism suggested by Mosier et al., 1995. Studies have shown that incorporation of crop residues of the preceding crop has significant impact on $N_2O$ emission in following crop growing season (Zou et al., 2005a; Drury et al., 2008). Several studies have reported that incorporation of crop residues in soil provides a source of readily available C and N, which influences $N_2O$ emissions (Khalil et al., 2007; Lou et al., 2007; Ma et al., 2009; Wang et al., 2010; Nishimura et al., 2011). Moreover previous studies have suggested that the mineralization of plant residues and thus the $N_2O$ emission depends on the C:N ratio (Zou et al., 2004; Klemedtsson et al., 2005). Huang et al. (2004) reported that residues with lower C:N ratio decompose faster and might provide a greater opportunity for producing more dissolved organic carbon, resulting in higher $N_2O$ emissions. In our study previous crop of rice grown in the experimental field might have provided more soluble C and N for nitrifying and denitrifying

organisms through decomposition of stubbles. Further, application of urea at the time of transplanting has increased soil $NO_3^-$ as substrate for denitrification under anaerobic condition resulting into emission peaks at 7 DAT in autumn rice ecosystem (Fig. 4.1). The observed emission peaks at active vegetative and panicle initiation stages (35, 49 DAT) in autumn rice ecosystem corresponds to topdressing of nitrogenous fertilizer in the form of urea at 30 DAT and 47 DAT, respectively (Fig 4.1). It has been reported that addition of inorganic nitrogen fertilizer promotes both nitrification and denitrification processes by increasing availability of nitrogen substrate for nitrifying and denitrifying microorganisms (Hou and Tsuruta, 2003; Steinbach and Alvarez, 2006; Zhang and Han, 2008). The observed emission peaks after fertilizer applications are attributed due to increased substrate ($NO_3^-$-N) for denitrification under anaerobic condition (Baruah et al., 2010a). This is evident from increased soil nitrate (Fig. 4.5) content of the experimental field at these stages irrespective of the rice ecosystems. Similarly, emission peaks observed at 35 and 56 DAT (after fertilizer urea application at 30 and 52 DAT) in monsoon (Fig. 4.12) and peaks at 35, 42, 63, 70 DAT (after top dressing of nitrogenous fertilizer urea at 30, 59 DAT) in summer rice ecosystem (Fig. 4.24) are contributed by high substrate availability in the form of soil nitrate (Fig. 4.15; 4.28). Increased $N_2O$ emissions were recorded from a rice-winter wheat rotation ecosystem following synthetic N fertilizer and crop residue application in southeast China by Zou et al. (2005b). Our findings are in agreement with the findings reported by several other researchers primarily higher $N_2O$ flux after nitrogen fertilizer application in agricultural fields (Yan et al., 2001; Wagner-Riddle et al., 2007; Barton et al., 2008; Dambreville et al., 2008; Alluvione et al., 2010). Luo et al. (2007) observed that urea induced stimulatory effect on $N_2O$ emission coincides with the increased soil nitrate concentrations and suggested that the accumulation of soil nitrate N induced by urea application provide a supply of substrate for denitrification, which is one of the major processes for $N_2O$ production (Carran et al., 1995; Castaldi and Smith, 1998; Bolan et al., 2004). Similarly, we also propose that increased $N_2O$ emissions after fertilizer application observed in our study are related to increased soil $NO_3^-$-N.

The emission peaks at crop maturity stage (70 DAT) in autumn rice ecosystems (Fig. 4.1) is due to higher soil $NO_3^-$ content of the experimental field. It

has been reported that soil nitrate acts as a pool of $N_2O$ precursor and senescence of older leaves and decomposition of crop roots provide an organic N source for $N_2O$ production in rhizosphere (Majumdar et al., 2002; Yang and Cai, 2005). The observed emission peaks at reproductive stage in monsoon (84 DAT) and summer (112 DAT) rice ecosystems (Fig. 4.12; 4.24) are associated with high $N_2O$ production in the rice rhizosphere as a result of decomposition of leaf litter and crop roots (Baruah et al., 2010b; Gogoi and Baruah, 2011b). Moreover, $N_2O$ emission at reproductive stage is also related to activity of denitrifying microorganisms in soil. It is also reported that incorporation of plant residues in soils increases the denitrification enzyme activity (Klemedtsson et al., 1991; Drury et al., 2004) and influence the composition and diversity of the denitrifying community (Nijburg et al., 1997) and thus effects $N_2O$ emissions. Similar mechanism might have promoted higher $N_2O$ flux at reproductive stage (70 DAT) under the influence of different doses of fertilizer applied in autumn rice crop land (Fig. 4.40; 4.41).

In rain-fed wheat growing season the emission peaks observed (Fig. 4.19) at 39 and 74 DAS (days after sowing) were contributed by hydrolysis of urea applied at 25 DAS i.e. at crown root initiation stage (Gogoi and Baruah, 2011b). In the present study, although the field was not irrigated the soil moisture content at time of fertilizer application was > 40% (Fig. 4.20). Similarly during irrigated wheat growing the first emission peaks appeared at 26 DAS in tested wheat varieties which coincides with fertilizer urea topdressing at 20 DAS followed by irrigation (Fig. 4.29). The emission peaks after fertilizer application is due to hydrolysis of applied urea to $NH_4^+$ and $NO_3^-$, the substrates for $N_2O$ production via nitrification and denitrification. It is reported that hydrolysis of applied urea influences nitrification through a transient rise in pH with subsequent denitrification leading to the formation and release of large amounts of $N_2O$ (Mulvaney et al., 1997; Khalil et al., 2002). Several studies have depicted the occurrence of $N_2O$ emission peaks following N fertilization as urea from wheat ecosystem (Panek et al., 2000; Bhatia et al., 2005; Wei et al., 2010) and it is documented that emission remains high for several weeks before returning to initial levels following fertilization (Conrad et al., 1983; VanCleemput et al., 1994). Wei et al. (2010) observed significant increase in $N_2O$ flux during the first 30 days after N fertilization. Increased $N_2O$ emission after fertilizer urea application was observed

from the day 1 and was noticeable during the first 2 weeks and reported to decrease subsequently (Kumar et al., 2000). Our results are in agreement with these findings showing emission peaks at 39 and 74 DAS (Fig. 4.19) in rain-fed and at 26 and 47 DAS in irrigated wheat (Fig. 4.29) after fertilizer urea application at 25 and 20 DAS in rain-fed and irrigated wheat, respectively. Emission peaks after panicle initiation and at crop ripening stage (81, 94 DAS in rain-fed and 82, 89 DAS in irrigated wheat) are attributed to increased soil $NO_3^-$-N (Fig. 4.23; 4.33) and soil organic carbon (Fig. 4.22; 4.32) of the experimental fields. Similar results of nitrogen fertilizer induced $N_2O$ emissions are reported (Wei et al., 2010) and they have observed that the effect of fertilization on temporal $N_2O$ fluxes in the wheat growing season are mainly associated with the activities of root and changes in water filled pore space which alter the C and N ratio of the soil. Decreased $N_2O$ fluxes recorded in our study at harvest are mainly due to decline in C and N sources available for microbial growth and because of growth retardation of the plants (Table 4.2; 4.9, 4.13; 4.16; 4.19; 4.27).

Seasonal integrated $N_2O$ emission ($E_{sif}$) varied significantly within varieties and in between various ecosystems (Table 4.3; 4.10; 4.14; 4.17; 4.20; 4.28). In present investigation the seasonal and temporal variations in $N_2O$ emission from different rice and wheat ecosystems are mainly due to the influence of soil and plant factors on $N_2O$ emission. These factors are soil water (Schindlbacher et al., 2004; Loecke and Robertson, 2009; Arriaga et al., 2010) soil $O_2$ status (Davidson and Schimel, 1995; Knowles, 2005; Mitsch et al., 2005) soil reaction (Feng et al., 2003; Kyveryga et al., 2004), temperature (Skiba and Smith, 2000; Holtan-Hartwig et al., 2001; Neto et al., 2011), presence of plants (Kirk and Kronzucker, 2005; Kuzyakov, 2006; Baruah et al., 2010a) metabolized carbon (Burford and Bremner, 1975; Chatterjee et al., 2008; Inagaki et al., 2008) and level and form of inorganic nitrogen (Drury et al., 2008; Dusenbury et al., 2008; Halvorson et al., 2008). The seasonal patterns of soil $N_2O$ fluxes are reported to be influenced by fertilization, wheat growth, and environmental conditions (Wei et al., 2010) and support our findings (Table 4.28). Significant variations in $N_2O$ emission among crop species and cropping system is also reported (Xiong et al., 2002) and similarly we also report variation in $N_2O$ emission in different cropping systems of rice and wheat. Agricultural $N_2O$ emissions are significantly influenced by N application rate, crop type, fertilizer type, soil organic C content, soil

pH, texture (Stehfest and Bouwman, 2006) and water regimes (Zou et al., 2009). Our findings of temporal and seasonal variations in $N_2O$ in relation to various factors such as SOC, soil $NO_3^-$-N, soil temperature and plant factors are in agreement with the studies mentioned above.

In the study with different doses and combinations of fertilizers we recorded higher seasonal $N_2O$ emissions (Table 4.28) when N, $P_2O_5$, $K_2O$ at the rate of 45:22:22 kg $ha^{-1}$ in the form of Urea, SSP, MOP + FYM ($T_9$) was applied followed by $T_7$ (N, $P_2O_5$, $K_2O$ @ 40:20:20 kg $ha^{-1}$ in the form of Urea, SSP, MOP + FYM) and $T_8$ (N, $P_2O_5$, $K_2O$ @ 35:18:18 kg $ha^{-1}$ in the form of Urea, SSP, MOP + FYM). Higher seasonal $N_2O$ emission in $T_9$ is attributed to more substrate availability ($NH_4^+$ and $NO_3^-$) for nitrifying and denitrifying microorganisms, which is contributed by higher dose of applied N in the form of urea. Applied farm yard manure (FYM) along with urea might have provided additional C and N substrates of nitrification and denitrification resulting in higher $N_2O$ fluxes (Fig 4.40g, h, i; 4.41g, h, i). Similar results of higher $N_2O$ emission after application of N fertilizers along with manure is reported elsewhere (Velthof et al., 2003). Application of manure and fertilizer increases the amount of mineral N in soil and leads to higher emission of $N_2O$ (Velthof et al., 2003). Mulvaney et al. (1997) suggested that the emission of $N_2$ and $N_2O$ was greater with alkaline-producing fertilizers than with acidic fertilizers. In our study relatively lower seasonal $N_2O$ emission recorded at $T_6$ (N, $P_2O_5$, $K_2O$ @ 45:22:22 kg $ha^{-1}$ as Urea, DAP, MOP), $T_4$ (N, $P_2O_5$, $K_2O$ @ 40:20:20 kg $ha^{-1}$ as Urea, DAP, MOP) and $T_5$ (N, $P_2O_5$, $K_2O$ @ 35:18:18 kg $ha^{-1}$ as Urea, DAP, MOP) is primarily due to lower soil alkalinity caused by $T_6$, $T_4$ and $T_5$ compared to $T_9$, $T_7$ and $T_8$ a mechanism suggested by Mulvaney et al. (1997). It is reported that more alkaline-producing fertilizers may promote denitrification under waterlogged conditions, either because of an increase in the supply of oxidizable C (Norman et al., 1987; Sen and Chalk, 1994) or because of a direct effect on microbial activity (Bollag et al., 1970). Similar mechanisms may have resulted increased $N_2O$ emissions in $T_9$, $T_7$ and $T_8$ in the present investigation. Efficient use of nutrients by rice plants (Magalhes et al., 1984; Monteny et al., 2006) can be a cause for observed lower seasonal emission (Table 4.28) in treatment $T_1$ (N, $P_2O_5$, $K_2O$ @ 40: 20: 20 kg $ha^{-1}$ as Urea, SSP, MOP).

**Relationship of soil factors with $N_2O$ emission from rice and wheat fields**

The production and emission of $N_2O$ from crop fields is influenced by various soil factors. Among these factors soil organic carbon (SOC) is considered to be a major factor influencing nitrification and denitrification reactions which simultaneously occurs in aerobic and anaerobic microsites of soil aggregate (Smith, 1990). SOC contents of the experimental fields in present study were initially low in all ecosystems (Fig. 4.4; 4.14; 4.22; 4.32; 4.44; 4.45). In rice and wheat ecosystems SOC increased considerably at active vegetative growth stage, panicle initiation stage, flowering and ripening stages. It is reported that denitrifiers as well as nitrifiers use organic C compounds as electron donors for energy and synthesis of cellular constituents (Tiedje, 1988; Azam et al., 2002). Since, nitrification is strongly influenced by $CO_2$ (Azam et al., 2005), while denitrification is driven by easily oxidizable C sources (Beauchamp et al., 1989) hence, both the processes of nitrification and denitrification are supported directly or indirectly by the availability of C (Gill et al., 2006). Moreover plants play an important role by releasing C through rhizodeposits (Gregory and Atwell, 1991; Kuzyakov and Domanski, 2000) and $CO_2$ by rhizorespiration (Kuzyakov and Domanski, 2002; Azam and Farooq, 2005; Kuzyakov, 2006) therefore higher SOC exert significant influence on the processes of nitrification and denitrification by affecting the activities of nitrifiers and denitrifiers (Gill et al., 2006). This mechanism does operate in our study where in positive correlations between $N_2O$ emission and SOC was observed (Table 4.1; 4.6; 4.11; 4.15; 4.18; 4.21). It is exclusively due to high C availability for nitrifiers and denitrifiers and similar relationship between SOC and $N_2O$ emission have been observed by several other workers (Millar and Baggs, 2005; Chatterjee et al., 2008; Inagaki et al., 2008; Wang et al., 2011). Increased SOC at active vegetative growth stage in our study is attributed to availability of a large quantity of decomposable organic matter and carbon from root exudates with increasing root biomass of the plants. It has been reported (Lu et al., 2000) that the dissolved organic carbon (DOC) in the rice rhizosphere is controlled by release of organic material from roots, which increased significantly with plant growth. Moreover, studies have indicated that roughly 30 to 60% of the net photosynthesized C is allocated below ground, and as much as 40 to 90% of this fraction enters the soil in the forms of root exudates, mucilage, sloughed-

off cells and decaying roots (Lynch and Whipps, 1990; Marschner, 1996). The increased $N_2O$ emissions with increasing SOC at active vegetative growth stages of rice and wheat is because of increased C in rhizosphere contributed by increased rate of plant growth parameters like roots, leaves and tillers (Table 4.2; 4.8; 4.13; 4.16; 4.27). It is also reported that the amount of DOC between rice flowering and maturation increases because the root exudation from rice plants reaches maximum at these stages (Holzapfel-Pschorn et al., 1986). This might be the possible reason of high SOC observed in our study at reproductive growth stage. Our results are in agreement with Wang et al. (2011) who have observed that an increase in $N_2O$ emission from 3.11 kg $Nha^{-1}$ $yr^{-1}$ to 4.43 kg $Nha^{-1}$ $yr^{-1}$ was because of increased soil organic carbon from 0.5% to 2%, in summer maize ecosystem. In laboratory incubation experiment Jager et al. (2011) observed higher $N_2O$ emission from farm yard manure treated soils. They suggested that the long-term application of farmyard manure and the associated increase in soil organic carbon and nitrogen stocks promote emissions of $N_2O$. Significant positive correlations (Table 4.21) of $N_2O$ emission and SOC in autumn rice with different doses and combinations of fertilizer treatment are associated with increased nitrification and denitrification of substrate in soil. Higher SOC observed in the field treated with $T_9$, $T_7$ and $T_8$ (Table 4.44; 4.45) are attributed to application of farm yard manure along with fertilizer N (urea) which might have increased SOC and stimulated $N_2O$ emission. Our results are in accordance with the findings of Jager et al. (2011) and Wang et al. (2011) mentioned above.

Soil $NO_3^-$-N and $N_2O$ emission in present investigation are found to be significantly correlated in the ecosystems (Table 4.1; 4.6; 4.10; 4.15; 4.18; 4.21). Soil $NO_3^-$-N contents of experimental fields were initially low and increased at active vegetative growth stage, crop ripening and maturity stage in rice ecosystems (Fig. 4.5; 4.15; 4.28; 4.46; 4.47). The main substrates for nitrification and denitrification in soils are $NH_4^+$ and $NO_3^-$, which may be derived from either decomposition of organic matter or the addition of fertilizers (Huang et al., 2004; Josileia et al., 2010; Soon et al., 2011). Relatively low soil $NO_3^-$ content of the rice fields at initial period is due to loss of $NO_3^-$ through denitrification under submerged soil condition. It is reported that in paddy soils alternate wetting and drying conditions create an ideal environment for denitrification. The nitrate formed during the dry period is rapidly lost through

denitrification when the soil is reflooded and a stimulation of decomposition of organic matter occurs (Reddy and Patrick, 1975; Sahrawat, 1980). Increased soil $NO_3^-$-N at active vegetative and panicle initiation stages is contributed by fertilizer urea topdressing at these stages in rice. In wheat ecosystems higher soil $NO_3^-$-N observed at active vegetative and panicle initiation stages is attributed by fertilizer urea application at crown root initiation stage (Fig. 4.23; 4.33). Higher soil $NO_3^-$-N at crop ripening and maturity stages were due to increased availability of mineralized soil organic nitrogen in soil as a result of decomposition of senesced older leaves and roots as suggested by Yang and Cai (2005). Plants can directly influence nitrate availability through uptake and assimilation of $NO_3^-$ making it unavailable to denitrification and subsequently with plant growth nitrate levels increases due to supply of organic matter of root origin (Pathak et al., 1999). The ability of rice plants to supply $O_2$ at the rhizosphere can enhance the nitrate content by promoting nitrification (Pathak et al., 1999) and then effect the soil environment for $N_2O$ production. Similar soil environment might have accelerated nitrification and denitrification processes leading to higher $N_2O$ emissions in rice ecosystems in present study. It is reported that total denitrification fluxes ($N_2O$ plus $N_2$) are directly proportional to soil $NO_3^-$ concentrations when a readily metabolisable organic substrate, is present (Wlodarczyk, 2000). When a lack of metabolisable organic matter limits potential denitrification, $N_2$ plus $N_2O$ fluxes do not increase with increasing $NO_3^-$ concentration a mechanism described by Sahrawat and Keeney (1986). In present investigation observed high organic carbon of experimental fields at reproductive stages has indicated that the organic substrate is not limiting for $N_2O$ production during crop growing season as suggested by Sahrawat and Keeney (1986) and Wlodarczyk (2000). The substrate inhibition (i.e., by $NO_3^-$) of $N_2O$ reductase a mechanism suggested by Zumft and Kroneck (1990) may also operate in our study contributing to more $N_2O$ emission. We therefore propose that the observed positive correlation between soil $NO_3^-$-N and $N_2O$ emission is related to substrate inhibition of $N_2O$ reductase enzyme.

With different doses and composition of fertilizer treatments higher dose of urea applied along with additional N in the form of FYM (Farm yard manure) in treatments $T_9$ $T_7$ and $T_8$ might have contributed to increased soil $NO_3^-$-N as evident

from high soil $NO_3^-$-N content of experimental field at different crop growing stages under the influence of treatment $T_9$, $T_7$ and $T_8$ (Fig. 4.46; 4.47). It is reported that the quantity of N applied, its source, and timing of application can potentially influence the magnitude of $N_2O$ emissions (McSwiney and Robertson, 2005). At low levels of soil N, competition between plant uptake and soil microbes favors plant assimilation hence low $N_2O$ is produced than at higher fertilizer concentrations (McSwiney and Robertson, 2005). Similar interaction between soil microbes and plants have contributed to higher $N_2O$ emissions with increasing soil $NO_3^-$-N under the influence of N fertilization in this study.

Soil temperature of the experimental fields under summer rice, rain-fed and irrigated wheat ecosystems showed significant positive relationship with $N_2O$ emission (Table 4.11; 4.15; 4.18). Soil temperature is considered to be a key variable that affects the emission rates of $N_2O$ (Firestone and Davidson, 1989). Rates of enzymatic processes related to nitrification and denitrification generally increase with temperature (Skiba et al., 1998) is the reason of observed increased emission with increasing soil temperature. Studies have shown that soil $N_2O$ emissions are enhanced by temperature, whereas at low temperature other factors, such as soil N availability and water content, play a controlling role (Sehy et al., 2003; Lee et al., 2008; Gogoi and Baruah, 2011a). A rise in temperature also affects soil respiration and anaerobicity thus influences denitrification rates and $N_2O$ emission (Smith, 1997). Although we have not studied the enzyme activities; but these might be the reasons of increased $N_2O$ emissions with increased soil temperature. In our study soil temperature (Fig. 4.3; 4.13; 4.21; 4.26; 4.31; 4.43) lies within a favorable range (17°C to 35°C) stimulating both nitrification and denitrification reactions (Holtan-Hartwig et al., 2001). Significant positive correlations of soil temperature with $N_2O$ emission in our study may be due to increased rates of organic matter decomposition with increasing soil temperature, which is evident from higher SOC value obtained during active vegetative and reproductive growth stages of rice and wheat. Our findings are in agreement with Neto et al. (2011) who reported an increased $N_2O$ emission from tropical forest ecosystem due to increased air and soil temperatures which resulted in increased decomposition of litterfall. Similar results of increased $N_2O$ emission rates with increasing soil temperature are reported earlier (Conen et al., 2000; Dobbie and

Smith, 2003; Saggar et al., 2004; Zou et al., 2004; Toma et al., 2007; Rafique et al., 2011).

Water levels of experimental fields were initially high in all rice growing ecosystems and declined at harvest (Fig. 4.2; 4.13; 4.25; 4.42). It has been reported that soil water can directly and indirectly influence $N_2O$ emission by influencing nitrification and denitrification processes by 1) providing suitable conditions for microbial growth and activity; 2) restricting supply of $O_2$ to micro-sites by filling soil pores; 3) releasing the available carbon and nitrogen from soil organic matter; and 4) providing a diffusion medium through which substrates and products are moved to and away from soil microorganisms (Aulakh et al., 1992; Pathak, 1999). In present investigation the water level of the experimental field in autumn rice ecosystem exhibited negative correlation with $N_2O$ emission (Table 4.1). Relatively low $N_2O$ emission observed up to 28 DAT in autumn rice ecosystem may be due to high standing water of the experimental field (Fig. 4.2). During this period $N_2O$ might have reduced into $N_2$ in the absence of $O_2$ resulting into less $N_2O$ production. It is reported that maximum $N_2O$ is produced when $O_2$ concentrations are low enough to promote reduction of $NO_3$, but not so low as to promote reduction of $N_2O$ to $N_2$ as $O_2$ is known to inhibit nitrous oxide reductase (Davidson and Schimel, 1995). The observed negative correlations between $N_2O$ emission and water level in rice ecosystems are attributed to reduction of $N_2O$ to $N_2$ when $O_2$ concentrations are lowered under flooded soil conditions facilitating the reduction process of $N_2O$ to $N_2$. At 49 DAT in autumn rice soil was partially aerobic due to draining of standing water and hence during this period both nitrification and denitrification reactions might have occurred simultaneously, leading to higher $N_2O$ flux (Fig. 4.1; 4.2). It is reported that in rice rhizosphere due to natural drainage, the upper layers of soil may remain aerobic for a significant period and $N_2O$ may be produced via nitrification and simultaneously denitrification may occur in lower horizons (Azam et al., 2002; Ghosh et al., 2003; Knowles, 2005; Mitsch et al., 2005). Our results are in accordance with reports from elsewhere showing decreased $N_2O$ emissions from high water regime paddy fields (Xu et al., 1997; Zou et al., 2005a; Singurindy et al., 2009). Previous studies have shown that nitrification rates increase with soil moisture up to 60% water-filled pore space (Linn and Doran, 1984). As water filled pore space (WFPS) exceeds 60%,

availability of $O_2$ and $CO_2$ substrate for nitrifiers declines due to severely restricted diffusion rates (Davidson and Schimel, 1995) and nitrification declines. Denitrification generally occurs when the soil water content is high enough to restrict the supply of $O_2$ via diffusion (Hutchinson and Davidson, 1993). Thus, denitrification is usually associated with soil water content above 60 % WFPS (Davidson, 1991). However, in present investigation we could not find a significant relationship between $N_2O$ emission and soil moisture (Table 4.11; 4.18).

Soil pH is one of the important factors influencing both nitrification and denitrification (Kyveryga et al., 2004). It has been reported that most nitrifying and denitrifying bacteria have optimum pH for growth between 6 and 8 (Paul and Clark, 1989; Pathak, 1999). Although soil pH and $N_2O$ emission in various ecosystems are not significantly correlated in present investigation the observed soil pH lies in between 5.0 to 6.5 ( Fig. 4.6; 4.16; 4.34, 4.48) which is considered to be suitable for nitrification and denitrification as reported by Goodroad and Keeney (1984). This revealed that a favorable soil condition persisted during the crop growth irrespective of ecosystems supporting both nitrifying and denitrifying reactions and $N_2O$ emission.

**Plant factors and $N_2O$ emission**

In the present investigation plant growth parameters such as shoot and root biomass, leaf area, root length and volume, tiller numbers and leaf numbers have shown significant positive correlations with $N_2O$ emissions in rice ecosystems (Table 4.1; 4.6; 4.15; 4.21). The observed lower $N_2O$ emission rates during initial stage of the plant growth is because of lower transport capacity of the plants at this stage which is apparent from less tiller number, leaf number, leaf area and root growth. It is reported that rice plants act as an effective pathway for $N_2O$ transport through aerenchyma cells in submerged soils (Xu et al., 2001) and during day time transport of $N_2O$ from roots to shoots is reported to take place within the transpiration stream and release through open stomata a mechanism suggested by Ferch and Romheld (2001) in sunflower. Increased leaf area and root growth with increasing plant growth at active vegetative and reproductive stages might have contributed to higher $N_2O$ transport and

emissions through open stomata's as suggested above (Ferch and Romheld, 2001; Baruah et al., 2011). Similarly in rain-fed wheat ecosystem observed higher emission at active vegetative and reproductive growth stage is attributed to increased shoot and root biomass of wheat varieties an evident from observed significant positive correlations of $N_2O$ emission with shoot and root biomass (Table 4.11). Higher stomatal frequency with increased leaf area accompanied by increased transpirational rate may have facilitated more transport of $N_2O$ to the atmosphere through the wheat plants by acting as an effective pathway which is evident from observed significant relationship between rate of transpiration and $N_2O$ emission in irrigated wheat ecosystem (Table 4.18). The positive correlation of $N_2O$ emission with transpiration rate of the wheat varieties in the present study is supported by the findings of Ferch and Romheld (2001). Recorded higher $N_2O$ emission from HUW 234 and DBW 14 is related to high transpiration rate of these varieties during different growth stages (Table 4.19). Similar observations of $N_2O$ transport within the transpiration stream to leaves were reported by Chang et al. (1998) and Pihlatie et al. (2005). Considering the movement of $N_2O$ along with transpiration stream, the size of the xylem may play an important role in its emission in wheat where aerenchymas are not available. Further investigation on relationship of anatomical characteristics like size of xylem with $N_2O$ transport are essential in wheat. Increased $N_2O$ emission rates with increasing root biomass observed in present investigation is possibly because of great surface area for diffusion of these gases into roots. It is reported that plants can serve as a conduit for dissolved gases from the root zone to the atmosphere and nitrous oxide as a water soluble molecule can hence be taken up by plant roots and transported to leaves via the transpiration stream (Yan et al., 2000). It is reported that increasing root length helps in nitrification process by supplying sufficient $O_2$ to the rhizosphere and then increases the $NO_3^-$ content in the rice rhizosphere (Pathak, 1999). A similar mechanism may contribute to higher seasonal $N_2O$ emission in the varieties with more root and shoot biomass (Table 4.3; 4.9; 4.10; 4.16; 4.17; 4.24; 4.28; Fig. 4.10; 4.11). Varietal differences in $N_2O$ emission are also reported from rice ecosystem by Ghosh and Kashyap (2003). These differences are reported to be as a result of influence of different cultivars on N- mineralization, nitrification and nitrifier population. According to them the observed variations in nitrifier population across the rice

cultivars are attributed to genotypic variations in enrichment of soil organic matter by these cultivars. The extent of aerobic conditions created in the soil in response to variations in root porosity of the plant system may also influence the $N_2O$ emission. Similarly genotypic variations in cultivars may have influenced soil organic matter, microbial population and finally influencing the $N_2O$ emission in present investigation.

The observed significant differences in seasonal $N_2O$ emission within varieties are attributed to variations in soil C input by root turnover and exudates suggested by many workers (Kuzyakov and Domanski, 2000; Millar and Baggs, 2005; Henry et al., 2008). The main C inputs into soil are reported to be of plant origin. These C compounds can enter soil directly from above ground and below-ground plant sources (Michalzik et al., 2001). In many agricultural systems where the above ground portion of the crop is removed, the dominant C inputs to the soil will be from root turnover and exudates (Jones et al., 2004). It has been suggested that about 10% to 15% of belowground allocated carbon is respired by roots, and about 15% to 25% of belowground allocated carbon is exuded from roots into the soil (Kuzyakov and Domanski, 2000). Rhizosphere microorganisms utilize these substances as easily available C and energy sources for fast growth and reproduction. All these organic matter significantly influence the soil microbial nitrification and denitrification, and hence $N_2O$ emission. Chen and Huang (2006) reported that root biomass is closely correlated with soil nitrification rate in wheat fields and nitrification is affected by rhizodeposition and root growth which enhances the process of nitrification. Similar mechanism might have contributed to variations in soil C input induced by root growth and hence differences in seasonal $N_2O$ emissions with plant growth are observed in our study.

**Crop yield and $N_2O$ emission**

In present investigation traditional rice varieties (Siana, Phorma in autumn rice; Rashmisali, Lalkalamdani, Choimora, Bogajoha, Basmuthi in monsoon rice ecosystem) with higher seasonal integrated nitrous oxide emission flux have shown

lower grain yield (Table 4.3; 4.10). These low yielding varieties have higher sterile grains panicle$^{-1}$ and recorded lower thousand grain weight (Table 4.3; 4.10) and are characterized by higher vegetative growth in terms of tillering, leaf area development, leaf number and root dry weights accumulation (Table 4.2; 4.7; 4.8; 4.9; Fig. 4.7; 4.10; 4.11). In high $N_2O$ emitting varieties, major portion of photosynthates are translocated towards the vegetative parts, as evident from the higher root and shoot growth and lesser amount to grains. Reported less grain yield in high $N_2O$ emitting rice varieties may follow a mechanism suggested by Das and Baruah (2008) and Baruah et al. (2010b). Similarly maximum yield was recorded from rice variety Kanaklata which is a low $N_2O$ emitting variety grown in summer rice ecosystem (Table 4.17). An inverse relationship between photosynthate partitioning to the grains and green house gas emission have been reported in number of studies (Sass and Cicerone, 2002; Denier van der Gon et al., 2002; Das and Baruah, 2008; Baruah et al., 2010b). Our observations are in agreement with the findings of the above mentioned researchers for an inverse relationship between green house gas emission and grain yield. Under rain-fed and irrigated ecosystems wheat variety HUW 234 showed higher seasonal integrated $N_2O$ emission followed by DBW 14, HUW 468 and Sonalika. In both the ecosystems maximum yield was recorded from wheat variety DBW 14 followed by Sonalika, HUW 234 and HUW 468 (Table 4.14; 4.20). In wheat ecosystem unlike rice ecosystem the inverse relationship between $N_2O$ emission and grain yield was not observed. The variations in yield potential of these varieties may be due to different degrees of photosynthate allocation to the grains which is governed by differences in phloem loading and unloading efficiency. Wang et al. (1997) reported that source-sink relationship is influenced by both genotype and environmental factors and may contribute to variation in photosynthesis and photosynthate partitioning of wheat. Internal plant factors may also influence photosynthate partitioning efficiency. The enzyme sucrose phosphate synthase (SPS) is reported to be closely associated with sucrose production as well as assimilate export from leaves (Huber et al., 1984, Sujatha et al., 2008). Investigation of the phloem anatomy and more particularly the phloem size may help in establishing a relationship of $N_2O$ emission with photosynthate allocation in wheat. Rice varieties under different fertilizers treatments showed maximum yield in $T_7$ followed by $T_1$, $T_4$,

$T_6$, $T_3$, $T_9$, $T_8$, $T_5$ and $T_2$ (Table 4.28). In present study although significant difference in yield could not be observed in $T_7$ (N, $P_2O_5$, $K_2O$ @ 40:20:20 kg $ha^{-1}$ as Urea, SSP, MOP +FYM) and $T_1$ (N, $P_2O_5$, $K_2O$ @ 40: 20: 20 kg $ha^{-1}$ in the form of Urea, SSP, MOP) in rice varieties Siana and Phorma (Table 4.28), the seasonal $N_2O$ emission is significantly reduced due to treatment $T_1$ compared to $T_7$. The reason of this reduced seasonal $N_2O$ emission in $T_1$ than $T_7$ is explained elsewhere (page, 164). Similarly in both the varieties there was no significant difference in yield between the treatments $T_4$ (N, $P_2O_5$, $K_2O$ @ 40:20:20 kg $ha^{-1}$ as Urea, DAP, MOP) and $T_6$ (N, $P_2O_5$, $K_2O$ @ 45:22:22 kg $ha^{-1}$ as Urea, DAP, MOP), but seasonal $N_2O$ emission is significantly lower in $T_4$ than $T_6$ (Table 4.28). Our results are in agreement with earlier study (Abdalla et al., 2010) which reported that a significant reduction in $N_2O$ emissions from the soil would be possible by reducing N fertilizer application in the order of 50% without critically altering grain yield or quality. This suggests that $N_2O$ flux has a threshold response to N fertilization where the amount of N lost to the atmosphere depends on the amount of N taken up by the crop. The varietal response to different level of fertilizer for yield extrusion and $N_2O$ emission will also depend upon nitrogen use efficiency by the crop (Huang and Tang, 2010). Exceeding this threshold value results in a higher release of $N_2O$ to the atmosphere (McSwiney and Robertson, 2005). However, applying N fertilizer according to soil N reserves, and matching the time of application to crop uptake can significantly reduce $N_2O$ emissions without affecting the crop yield (Wagner-Riddle et al., 2007). Our results of increasing $N_2O$ emissions with increased N fertilizer dose without differences in production potential are in agreement with the findings of previous studies (Tilman et al., 2002; Cassman et al., 2003; Galloway et al., 2003). It is reported that the increasing input of synthetic fertilizer cannot promise a substantial increase in crop productivity because of diminishing returns, but can increase $N_2O$ emissions (Mosier and Kroeze, 2000; McSwiney and Robertson, 2005). Sehy et al. (2003) observed 34% decreases in $N_2O$ flux with decreasing fertilizer application from 150 to 125 kg N $ha^{-1}$ with no detrimental effect on yield. Similarly significant difference in yield of rice in the treatments $T_3$ (N, $P_2O_5$, $K_2O$ @ 45:22:22 kg $ha^{-1}$ as Urea, SSP, MOP), $T_9$ (N, $P_2O_5$, $K_2O$ @ 45:22:22 kg $ha^{-1}$ as Urea, SSP, MOP + FYM), $T_8$ (N, $P_2O_5$, $K_2O$ @ 35:18:18 kg $ha^{-1}$ as Urea, SSP, MOP + FYM) could not be obtained but differences in seasonal

$N_2O$ emission were observed (Table 4.28) which might be due to differences in fertilizer doses and combinations as suggested by the above researchers (Tilman et al., 2002; Cassman et al., 2003; Galloway et al., 2003; Abdalla et al., 2010). From these findings we can suggest that $T_1$ (N, $P_2O_5$, $K_2O$ @ 40: 20: 20 kg $ha^{-1}$ in the form of Urea, SSP, MOP) without any organic amendment can be recommended for sustaining productivity and as well for lower $N_2O$ emission. This is in agreement with Hoben et al., 2011, who has suggested that the potential to lower agricultural $N_2O$ fluxes within a range of N fertilization be selected which do not affect the economic return from grain yield "a balance between environmental issue and agricultural productivity".

# Chapter 6
# SUMMARY AND CONCLUSION

# 6. SUMMARY AND CONCLUSION

Experiments were conducted in North Bank Plain Agroclimatic Zone of Assam, India to measure seasonal and temporal patterns of $N_2O$ emissions from rice and wheat ecosystems. Efforts were also made to investigate the relationship of plant growth parameters and soil parameters with $N_2O$ emissions from rice and wheat ecosystems. Further suitable form and dose of nitrogenous fertilizer was identified for reducing $N_2O$ emissions from agricultural field in this zone. The salient findings observed during the experiments are summarized blow.

1. In present investigation regardless of varietal differences similar pattern of $N_2O$ emission was observed in rice and wheat ecosystems. Low emissions were observed during early vegetative growth period which increased considerably at active vegetative growth stage and reproductive stage and declined at harvest. There was co-incidence of emission peak with time of fertilizer application.

2. $N_2O$ emission estimation from autumn rice (*Ahu*) ecosystem indicated higher seasonal integrated emission ($E_{sif}$) from rice varieties Phorma (150.30 mg $N_2O$-N $m^{-2}$) and Siana (139.19 mg $N_2O$-N $m^{-2}$) followed by Luit (99.97 mg $N_2O$-N $m^{-2}$), Kapilli (84.68 mg $N_2O$-N $m^{-2}$) and Disang (77.14 mg $N_2O$-N $m^{-2}$).

3. In monsoon rice (*Sali*) ecosystem traditional rice varieties Basmuthi (189.46 mg $N_2O$-N $m^{-2}$) followed by Bogajoha (174.80 mg $N_2O$-N $m^{-2}$) recorded maximum seasonal $N_2O$ emission. High yielding modern varieties Gitesh and Kushal recorded less seasonal $N_2O$ emission among the varieties.

4. $N_2O$ emission estimation from summer rice (*Boro*) ecosystem recorded maximum seasonal $N_2O$ emission from variety Joymoti (216.37 mg $N_2O$-N $m^{-2}$) followed by Bishnuprasad (206.29 mg $N_2O$-N $m^{-2}$) and Kanaklata (190.11 mg $N_2O$-N $m^{-2}$).

5. Among the rice growing ecosystems maximum seasonal integrated nitrous oxide emission ($E_{sif}$) was recorded from summer rice (*Boro*) ecosystem followed by monsoon (*Sali*) and autumn (*Ahu*) rice ecosystem.

6. The relationship of $N_2O$ emission with plant growth parameters like leaf area, leaf number, tiller number, root length, shoot biomass, root biomass and soil organic carbon, soil nitrate content, soil temperature etc, from rice ecosystems was significant.

7. Among the variables root and shoot weight, soil $NO_3^-$-N and field water level are identified as main driving properties influencing $N_2O$ emission in autumn rice ecosystem (through factor analysis). Whereas the soil $NO_3^-$-N, leaf area and soil organic carbon were identified as main driving properties in summer rice.

8. Grain yield was higher in low $N_2O$ emitting rice varieties irrespective of the ecosystems.

9. Rice varieties Disang, Luit and Kapilli having low seasonal $N_2O$ emission and high yield potential are identified as suitable varieties for cultivation in autumn rice ecosystem of Assam.

10. Varieties Gitesh, Kushal with higher grain yield potential and lower $N_2O$ emission are identified as suitable varieties for cultivation in winter rice ecosystem and variety Kanaklata for summer rice ecosystem.

11. $N_2O$ emission from varieties HUW 234, DBW 14 and HUW 468 was higher in both rain-fed and irrigated wheat ecosystem. Wheat variety Sonalika was identified to be low $N_2O$ emitting variety.

12. $N_2O$ emission is found to have correlation with soil organic carbon (SOC), soil $NO_3^-$-N, soil temperature, shoot dry weight and root dry weight in rain-fed wheat ecosystem. However, the soil temperature followed by SOC and soil $NO_3^-$-N were considered as important variables (through factor analysis) influencing $N_2O$ emission.

13. $N_2O$ emission from irrigated wheat ecosystem showed positive relationship with soil organic carbon, soil $NO_3^-$-N, soil temperature and transpiration rate.

14. In both rain-fed and irrigated wheat ecosystems maximum yield was recorded in the DBW 14 followed by Sonalika, HUW 234 and HUW 468.

15. Wheat variety Sonalika with yield potential of 30.44 q $ha^{-1}$ under rain-fed and 31.76 q $ha^{-1}$ under irrigated ecosystem is found to be suitable for cultivation at North Bank Plain Agroclimatic zone for reducing $N_2O$ emission and higher productivity.

16. Maximum seasonal $N_2O$ emission was recorded from the rice varieties when fertilizers were applied at the rate of 45:22:22 kg N-$P_2O_5$-$K_2O$ $ha^{-1}$ in the form of urea, single super phosphate and muriate of potash along with FYM ($T_9$) followed by N, $P_2O_5$, $K_2O$ @ 40:20:20 kg $ha^{-1}$ as Urea, SSP, MOP + FYM

($T_7$) and N, $P_2O_5$, $K_2O$ @ 35:18:18 kg $ha^{-1}$ as Urea, SSP, MOP + FYM ($T_8$). Emission was significantly lower for the varieties when grown in 35:18:18 kg N-$P_2O_5$-$K_2O$ $ha^{-1}$ ($T_2$) fertilizers in the form of Urea, SSP, and MOP. Variety Phorma recorded higher seasonal emission compared to Luit when grown in different level of fertilizer application in soil.

17. Maximum yield was recorded under fertilizer treatment $T_7$ (N, $P_2O_5$, $K_2O$ @ 40:20:20 kg $ha^{-1}$ as Urea, SSP, MOP + FYM) followed by $T_1$ (N, $P_2O_5$, $K_2O$ @ 40: 20: 20 kg $ha^{-1}$ as Urea, SSP, MOP), $T_4$ (N, $P_2O_5$, $K_2O$ @ 40:20:20 kg $ha^{-1}$ as Urea, DAP, MOP), $T_6$ (N, $P_2O_5$, $K_2O$ @ 45:22:22 kg $ha^{-1}$ as Urea, DAP, MOP), $T_3$ (N, $P_2O_5$, $K_2O$ @ 45:22:22 kg $ha^{-1}$ as Urea, SSP, MOP), $T_9$ (N, $P_2O_5$, $K_2O$ @ 45:22:22 kg $ha^{-1}$ as Urea, SSP, MOP + FYM), $T_8$ (N, $P_2O_5$, $K_2O$ @ 35:18:18 kg $ha^{-1}$ as Urea, SSP, MOP + FYM), $T_5$ (N, $P_2O_5$, $K_2O$ @ 35:18:18 kg $ha^{-1}$ as Urea, DAP, MOP) and $T_2$ (N, $P_2O_5$, $K_2O$ @ 35:18:18 kg $ha^{-1}$ as Urea, SSP, MOP) in both the varieties.

18. $N_2O$ emission estimation under the influence of different level of fertilizer application revealed that $T_1$ (N, $P_2O_5$, $K_2O$ @ 40: 20: 20 kg $ha^{-1}$ as Urea, SSP, MOP without any organic amendment) with yield potential of 29.03 q $ha^{-1}$ can be suitably used in autumn rice ecosystem at North Bank Plain Agroclimatic Zone of Assam for reducing $N_2O$ emission and for higher productivity.

The experiments on $N_2O$ emission from various rice and wheat ecosystems revealed wide fluctuations in $N_2O$ emission rates among different varieties at various growth stages. These differences in $N_2O$ emission among varieties are primarily because of differences in growth physiology which influences $N_2O$ transport and emission. $N_2O$ emission estimation from rice ecosystems showed significant relationship with plant and soil variables. Whereas, in wheat soil variables along with plant transpirational rate is found to be significantly related to $N_2O$ emission. Important plant and soil variables identified to be associated with $N_2O$ emissions in the present study may help in the understanding of the mechanisms of $N_2O$ transport

and regulations to the atmosphere. Irrespective of rice ecosystems low seasonal $N_2O$ emitting rice varieties have shown higher grain yield and based on these information's the rice varieties with lower $N_2O$ emission and high yield potential are identified in the present study for cultivation in this zone. In wheat ecosystems Sonalika is found to be low $N_2O$ emitting with high yield potential in both the ecosystems. These varieties can also be used by plant breeders in variety improvement programme to develop low greenhouse gas emitting varieties. The significant positive correlation of leaf transpiration rate with $N_2O$ emission in irrigated wheat ecosystem suggests that movement of $N_2O$ along with the transpirational water flow may be an important mechanism of $N_2O$ transport and emission through wheat plants. $N_2O$ emission estimation from autumn rice ecosystem with different fertilizer treatments revealed that fertilizer dose and combination significantly influence seasonal $N_2O$ emission. In present study the seasonal $N_2O$ emission was significantly lowered in $T_1$ (N, $P_2O_5$, $K_2O$ @ 40: 20: 20 kg $ha^{-1}$ as Urea, SSP, MOP). Based on these observations it can be suggested that biological mitigation strategy can be developed if suitable rice and wheat genotypes are selected on the basis of plant growth parameters, soil properties, emission characteristics and yield potential. Selection of suitable fertilizer dose and composition can significantly lower emission without affecting the grain yield.

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# APPENDIX

# List of Publications

Baruah, K.K., Gogoi, B., Gogoi, P. & Gupta, P.K. $N_2O$ emission in relation to plant and soil properties and yield of rice varieties, *Agron. Sustain. Develop.* **30** (4), 733--742, 2010 (EDP Sciences).

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Gogoi, B. & Baruah K.K. Nitrous oxide emission from tea (*Camellia sinensis* (L.) O. kuntze)-planted soils of North East India and soil parameters associated with the emission, *Current Sci.* **101**(4), 531--536, 2011.

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Baruah, K.K., Gogoi Boby, Borah Leena, Gogoi Manoshi, & Boruah, R. Plant morphophysiological and anatomical factors associated with nitrous oxide flux from wheat (*Triticum aestivum*), *J. Plant Research*, 2011, DOI: 10.1007/s10265-011-0464-4, in press.

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Research article

# $N_2O$ emission in relation to plant and soil properties and yield of rice varieties

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**Abstract** – Nitrous oxide ($N_2O$) is a major greenhouse gas contributing to global warming Rainfed rice fields are considered to be a notable source of atmospheric $N_2O$ emission To investigate the dynamics of $N_2O$ emission and the relationship of plant and soil properties with emission of $N_2O$ in rice a field experiment was conducted The five popularly grown rice varieties Luit, Disang, Kapili, Siana and Phorma were grown in the fall season under rainfed conditions $N_2O$ emission was measured at seven-day intervals starting from the day of transplanting for the whole crop growing season We also measured soil parameters e g soil pH, soil temperature, soil organic carbon soil $NO_3^-$-N, and field water level and plant growth parameters root-shoot dry weight, root length and leaf area Our results show that $N_2O$ emission from the plant varieties ranged from 1 24 μg to 379 40 μg $N_2O$-N $m^{-2}$ $h^{-1}$ Seasonal $N_2O$ emission from the rice varieties ranged from 77 to 150 mg $N_2O$-N $m^{-2}$ Root dry weight, shoot dry weight soil $NO_3^-$-N, root length leaf area and field water showed relationships with $N_2O$ emission Root and shoot weight, soil $NO_3^-$-N and field water were found to be the main factors influencing $N_2O$ emission The varieties Phorma and Siana, with lower grain productivity but profuse vegetative growth, showed higher seasonal $N_2O$ emission

**leaf area / nitrous oxide / rice ecosystem / grain yield**

## 1. INTRODUCTION

Global warming induced by increasing nitrous oxide concentration in the atmosphere is a matter of great environmental concern Its atmospheric concentration increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005 (IPCC, 2007) Nitrous oxide occurs in the atmosphere in minute quantities compared with other trace gases but its effectiveness in trapping infrared radiations from the Earth's surface is high (Duxbury and Mosier, 1993) More than one-third of all nitrous oxide emissions are anthropogenic and are primarily due to agriculture (IPCC, 2007) Nitrous oxide emission from agricultural sources includes direct emissions from fertilizer or manures applied to agricultural soils and indirect emissions from atmospheric nitrogen depositions, sewage and loss of nitrogen Production of $N_2O$ in the soil is a natural process and occurs primarily as a result of the microbial processes of nitrification and denitrification (Davidson and Schimel, 1995) Nitrification consists of the oxidation of ammonium ($NH_4^+$) into nitrite ($NO_2^-$) and then nitrate ($NO_3^-$) It is an aerobic process carried out by a few species of autotrophic bacteria A number of environmental factors such as substrate availability, soil water content, $O_2$ availability, soil pH and temperature have been identified to affect nitrification and denitrification In general, nitrification rates increase with soil moisture up to 60% water-filled pore space (WFPS) (Linn and Doran, 1984) As WFPS exceeds 60%, availability of $O_2$ and $CO_2$ substrate for nitrifiers declines due to severely restricted diffusion rates (Davidson and Schimel, 1995) Soil temperature and pH further regulate nitrification and $N_2O$ production Denitrification is the microbiological reduction of nitrate or nitrite into gaseous nitrogen, either as molecular nitrogen or as an oxide of nitrogen Denitrification mainly occurs when soil water and $NO_3^-$ contents are high and diffusion rates of $O_2$ into the soil are reduced Both nitrification and denitrification reactions depend on availability of oxidizable C in the soil, because the nitrifiers and denitrifiers use organic carbon compounds as electron donors for energy and synthesis of cellular constituents and growth of the denitrifiers (Tiedje et al , 1982) In most soils, denitrification activity increases rapidly when WFPS exceeds 70% due to the lack of $O_2$ Maximum $N_2O$ is produced when $O_2$ concentrations are low enough to promote reduction of $NO_3^-$, but not so low as to promote reduction of $N_2O$ into $N_2$ as $O_2$ is

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known to inhibit nitrous oxide reductase. Denitrification has been observed at temperatures near freezing and as high as 70 °C (Holtan-Hartwig et al., 2001). Numerous studies have shown increases in soil $N_2O$ emissions following N fertilizer application (Aulakh et al., 2001; Hao et al., 2001). Application of urea- or ammonium-based fertilizers has been associated with elevated $N_2O$ emissions under conditions favoring nitrification and denitrification, such as moist, well-aerated soils. Nitrate-N fertilizer sources may exacerbate emissions where denitrification is favored, such as in waterlogged soils. Not only the N of applied urea but also the mineralized soil organic N is a source of $N_2O$ production in soil, which is released from decomposition of soil organic matter. Rice is reported to transport $N_2O$ produced in submerged soil into the atmosphere via aerenchyma (Xu et al., 2001). The role of growing plants in nitrogen-fertilized agricultural fields in $N_2O$ emissions is being assessed by many researchers. It has been elucidated that the availability of nitrate, labile C compounds and $O_2$ is greatly affected by the existence of growing plants and hence affects $N_2O$ production in soil. Contribution of rice plants to the emission of $N_2O$ from paddy soil is also reported by Mosier et al. (1990) and Yan et al. (2000). The main pathway of $N_2O$ transport is along the transpiration stream and is released through open stomata (Ferch and Romheld, 2001). The larger accumulation of biomass due to plant growth stimulation may increase the availability of C and N substrate in soil and hence accelerate $N_2O$ formation (Jiang et al., 2006). Therefore, plant genotypes may differ in their potential to release $N_2O$ in soil and further its transportation via plant cells. Improving N-use efficiency can drastically reduce $N_2O$ emissions. This includes optimum N supply to crops, proper management of crop and animal residues, use of controlled-release fertilizers, nitrification inhibitors and proper water management.

In a northeastern state of India, Assam, rice is the major cereal crop grown throughout the year under different ecosystems. At present, rice occupies about two-thirds of the total cropped area in the state. Being the single major source of agricultural gross domestic product, rice plays a significant role in the state economy. The area under rice cultivation has shown an increasing trend and this will contribute to the increasing trend of $N_2O$ emission from agricultural sources.

Although a few studies related to $N_2O$ emission from agricultural fields in India have been reported, no such studies have been conducted in Assam. Moreover, previous studies from the Indian subcontinent have not highlighted $N_2O$ emission in relation to plant growth properties. Therefore, the present study was conducted in a rainfed rice field planted with five rice varieties. The objectives of this study were to investigate the dynamics of $N_2O$ emission from rice agricultural soil and to work out the relationship of plant and soil properties with $N_2O$ emissions.

## 2. MATERIALS AND METHODS

### 2.1. Experimental site

The study was conducted in the North Bank Plain Agroclimatic Zone of Assam (26°41′ N, 92°50′ E) in Tezpur, India. The experimental site was located in a farmer's field about 6 km from the Tezpur University campus towards the west. The zone is humid subtropical and characterized by alluvial soils with sandy to sandy loam texture. During the experimental period from April 2006 to July 2006 the average weekly rainfall ranged from 0.17 mm to 12.37 mm. The average minimum and maximum air temperature ranged from 17.56 °C to 38.00 °C and the relative humidity 50–80%. The soil physico-chemical properties of the experimental site (0–15 cm depth) at the time of the experiment were: sand, 28.20 (%); silt, 41.60 (%); clay, 30.20 (%); bulk density, 0.86 (g $cm^{-3}$); cation exchange capacity, 10.15 (m eq. 100 $g^{-1}$); pH, 5.4; soil organic carbon, 0.93 (%), electrical conductivity, 0.45 (mmhos 100 $g^{-1}$); available nitrogen, 372.56 (kg $ha^{-1}$); available phosphorus, 35.19 (kg $ha^{-1}$); available potassium, 236.50 (kg $ha^{-1}$).

### 2.2. Plant cultivation

Seeds of five popularly grown rice varieties, namely Luit, Disang, Kapilli, (high-yielding varieties), Siana and Phorma (local varieties), were sown in the nursery bed on 3rd April, 2006. The main field, which remained fallow after the previous harvested rice crop from November, 2006 onward, was thoroughly plowed, laddered and puddled, and two seedlings per hill of each variety were transplanted on 4th May, 2006 on plots of size 6 m × 5 m, and replicated 3 times in a randomized block design at a spacing of 20 cm × 15 cm (row to row and plant to plant). The layout of the experiment is shown in Figure 1. All intercultural operations were done in agreement with conventional methods. Fertilizers were applied as per the package of practice of the Department of Agriculture, Government of Assam, India, at the rate of 40:20:20 kg $N$-$P_2O_5$-$K_2O$ per ha in the form of urea, single superphosphate and muriate of potash. One-third of the total dose of urea was applied at the time of final puddling before transplanting, along with the full dose of single superphosphate ($P_2O_5$) and muriate of potash ($K_2O$). The second and third doses of urea were applied at tillering and the panicle initiation stage, i.e. at 30 and 47 days after transplanting (DAT) of the crop. The crop was harvested on 22nd July, 2006.

### 2.3. Collection and analysis of gas samples

Gas samples were collected by a closed chamber technique (Buendia et al., 1997). Chambers of 50 cm × 30 cm × 70 cm (length × width × height) were made of 6-mm-thick acrylic sheets. The rectangular U-shaped aluminum channel (50 cm × 30 cm) supported on an aluminum frame (50 cm × 30 cm × 15 cm) was used to accommodate the chamber. The aluminum channel was pre-inserted into the soil to a depth of 15 cm well in advance (7 days before transplanting). Six hills of rice plants were enclosed inside the channel. During gas sampling, the aluminum tray was filled with water to a depth of 2.5 cm, which acted as an air seal when the perspex box was placed on the tray. A battery-operated fan was fixed inside the chamber

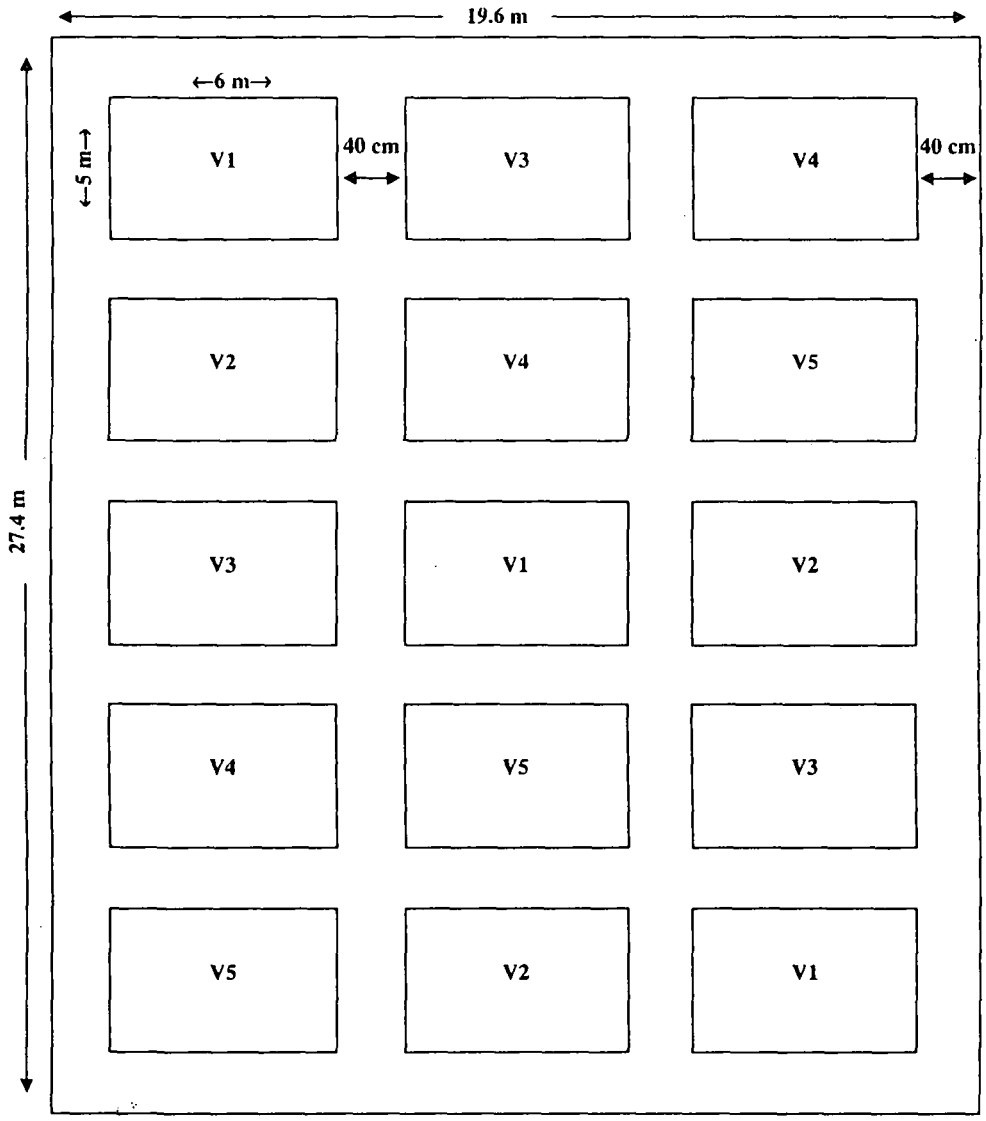


**Figure 1.** Layout of the experiment in field. Where, $V_1$ = Luit, $V_2$ = Disang, $V_3$ = Kapilli, $V_4$ = Siana $V_5$ = Phorma. Gross experimental area = 537.04 $m^2$.

to homogenize the air. A thermometer was inserted inside the acrylic box to record the box temperature. Barometric pressure and water level inside the chamber were measured during each sampling for calculating air volume at standard temperature and pressure. The gas samples were drawn with the help of a 50-mL airtight syringe fitted with a three-way stop cork at fixed intervals of 0, 15, 30 and 45 min, once in the morning at 09:00 h and again at 14:00 h. The samples were collected from the first date of transplanting of the crop until two weeks after harvest at seven-day intervals. Nitrous oxide concentrations in the gas samples were analyzed by a Varian model 3800 gas chromatograph (USA) fitted with an electron capture detector (ECD) and 6″ × 1/8″ stainless steel chromopack capillary column (50 cm long, 0.53 mm outside and 1μm inside diameter). Column, injector and detector temperatures were 80 °C, 200 °C and 300 °C, respectively. Carrier gas ($N_2$) with a flow rate of 15 ml $min^{-1}$ was used. The gas chromatograph was calibrated periodically by standard $N_2O$ obtained from the National Physical Laboratory, New Delhi. $N_2O$ flux was calculated according to the methods of Parashar et al. (1996). The average of morning and evening fluxes was considered as the flux value for the day and expressed as μg $N_2O$-N $m^{-2}$ $h^{-1}$. Cumulative $N_2O$ emission for the entire crop growth period was computed by the method given by Naser et al. (2007). Cumulative $N_2O$ emission is expressed as seasonal integrated flux ($E_{sif}$) in mg $N_2O$-N $m^{-2}$.

### 2.4. Plant parameter analysis

All plant growth parameters were measured at weekly intervals. Plant samples from each replication were uprooted

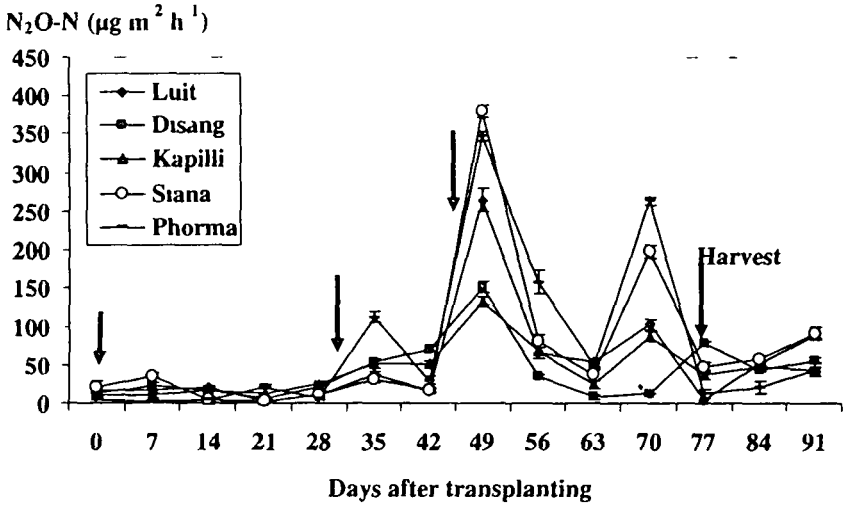


**Figure 2.** Nitrous oxide fluxes $N_2O$ N ($\mu g\ m^{-2}\ h^{-1}$) from rice varieties Emission peaks recorded at 35, 49 and 70 days after transplanting Vertical bars represent standard error of three replications (standard error values are multiplied by 5) The arrows indicate the time of application of fertilizer and day of harvest

and washed thoroughly with water, and the root and shoots were separated and dried at 75 ± 2 °C in an oven until a constant weight was observed and weighed Leaf area and root length were measured by a portable laser leaf area meter assembled with a root measurement attachment (CID, Model CI-203, USA) To calculate sterility (%) the number of unfilled grains out of total grains was counted from randomly selected panicles from each replication and expressed as a percentage Rice yield was determined from the total plot area by harvesting all the hills excluding the hills bordering the plots The grains were separated from straw, dried and weighed

### 2.5. Soil parameter analysis

Soil samples were collected at weekly intervals from a depth of 15 cm with the help of a soil sampling agar Samples collected from each plot were mixed thoroughly and made a composite sample for analysis Bulk density was determined by the core sampler method (Mishra and Ahmed, 1987) Available nitrogen, available phosphorus and available potassium content in the soil were determined by Kjeldahl's method, Bray's I method and flame photometric method, respectively (Jackson, 1973) Organic carbon was estimated by the wet digestion method of Walkley and Black (1947) Soil was treated with a known volume of standard $K_2Cr_2O_7$ solution in the presence of concentrated $H_2SO_4$ to produce nascent oxygen which oxidizes carbon into $CO_2$ The excess unused $K_2Cr_2O_7$ was titrated back against a standard solution of ferrous ammonium sulfate in the presence of orthophosphoric acid and NaF using a diphenylamine indicator At the end point of titration the color changes from blue to green Soil pH (1 2 5 soil water ratios) was measured using a Systronics Griph model D pH meter during each nitrous oxide sampling period Soil temperature was measured at 5 cm soil depth with a soil thermometer Soil nitrate-N content was determined by the method of Ghosh et al (1983) The standing water level of the experimental field was recorded at weekly intervals during gas sampling

### 2.6. Statistical analysis

Statistical analyses of the data were performed using the SPSS 10 0 software package The relationship between nitrous oxide fluxes with means of other plant and soil variables were determined by factor analysis The Varimax rotation method (an orthogonal rotation) was used in order to make each factor uniquely defined as a distinct cluster of intercorrelated variables The factor loadings of the rotated matrix, the percentage variability explained by each factor and the communalities for each variable were determined The significance of the difference of different parameters among the rice varieties were analyzed by two-way ANOVA and subsequently by Duncan's multiple range test

## 3. RESULTS AND DISCUSSION

The $N_2O$ emission from the rice varieties during the whole crop growing season varied from 1 24 $\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$ to 379 40 $\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$ (Fig 2) Similar patterns of $N_2O$ emission were observed from all rice varieties, which was initially low up to 28 DAT The observed minor $N_2O$ emission peaks at 7 DAT coincides with the basal application of nitrogenous fertilizer at the time of transplanting along with the mineralized soil organic nitrogen from the stubble of the previous season's crop (Mosier et al , 1995) Huang et al (2004) reported that mineralization of plant residues and thus the $N_2O$ emission depends on the C N ratio The residues with lower C N ratio decompose faster and might provide a greater opportunity for producing more dissolved organic carbon, resulting in higher $N_2O$ emissions The relatively low $N_2O$ emission

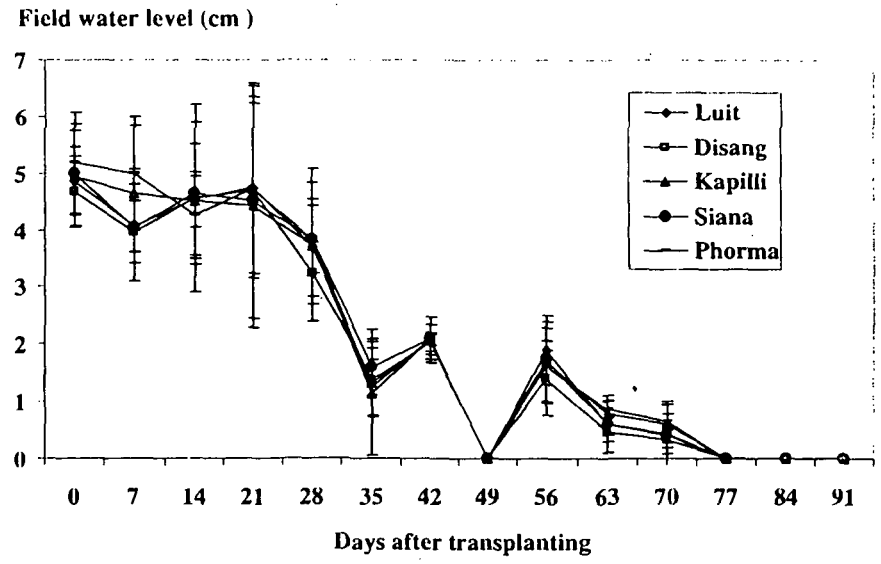


**Figure 3.** Standing water level of the experimental field during rice growing season. Vertical bars represent standard error of three replications (*standard error values are multiplied by 5*).

observed up to 28 DAT may be due to a high field water level (Fig. 3), which is substantiated by the high rainfall during this period. The water level of the experimental field ranged from 0.33 to 5.18 cm. Water level was initially high and decreased at harvest. A significant correlation ($R$ = −0.632, $P$ = 0.018) of water level of the experimental field with $N_2O$ emission was recorded. During this period $N_2O$ might have reduced into $N_2$ in the absence of $O_2$ (Davidson and Schimel, 1995). Thereafter, the rate of emission gradually increased in all the rice varieties and emission peaks were recorded at 35, 49 and 70 DAT, corresponding to the active vegetative, panicle initiation (PI) and maturity stages of the varieties (Fig. 2). The observed emission peak at 35 DAT corresponds to topdressing of nitrogenous fertilizer in the form of urea, which supplies the substrate ($NO_3^-$-N) for denitrification under anaerobic conditions. It has been reported that addition of inorganic nitrogen fertilizer promotes both nitrification and denitrification processes due to higher availability of nitrogen substrate for nitrifying and denitrifying microorganisms (Hou and Tsuruta, 2003; Steinbach and Alvarez, 2006). Similar emission peaks were observed at 49 DAT after application of urea at 47 DAT. During this period both nitrification and denitrification processes might have occurred simultaneously, because the soil was partially aerobic due to draining of standing water at 49 DAT. Increasing leaf area at this stage (Tab. II) with higher stomatal frequency accompanied by a faster transpirational rate may also have facilitated emission of $N_2O$ into the atmosphere through the rice plant, acting as an effective pathway for $N_2O$ transport. It has been reported that rice plants may act as an effective pathway for $N_2O$ transport through aerenchyma cells in submerged soils through open stomata (Mosier et al., 1990). A similar mechanism of emission might be the reason for the observed correlation of $N_2O$ emission and leaf area in the present study ($R$ = 0.620, $P$ = 0.021). In our study we also observed a significant correlation of shoot dry weight with $N_2O$ emission ($R$ = 0.527, $P$ = 0.048). The varieties Phorma and Siana showed higher leaf area and shoot dry weight compared with the other varieties (Tab. II), and these varieties recorded significantly higher seasonal integrated $N_2O$ flux (Tab. I). The varietal differences in leaf area and shoot dry weight and interaction effect between varieties and DAT were also found to be significant (Tab. II). This indicates that increased gas transport capacity with a larger plant canopy in terms of leaf area and shoot growth might have contributed to the higher emission rate from these varieties. Our findings are supported by Mosier et al. (1990) and Xu et al. (2001). A possible $N_2O$ transport through the plant body, with distinct $N_2O$ emission peaks at the flowering and ripening stages, were also observed by Chang et al. (1998).

During the crop growing season soil organic carbon content varied from 0.93% to 1.27%. The soil organic carbon content of the experimental field between 35 and 56 DAT (active vegetative growth stage and panicle initiation stage) was found to be higher, and thereafter it started to decrease (Fig. 4). The observed relationship between soil organic carbon and $N_2O$ emission is not significant in our study ($R$ = 0.397, $P$ = 0.113). We observed a significant correlation between root dry weight ($R$ = 0.565, $P$ = 0.035), root length ($R$ = 0.562, $P$ = 0.036) and $N_2O$ emission. The recorded root dry weight and root length of the varieties Phorma and Siana were significantly high (Tab. III).

Soil $NO_3^-$-N content of the experimental field was initially low. It started to increase from 35 DAT onwards and varied significantly (Tab. IV). The higher soil $NO_3^-$ content observed in the experimental field at the crop maturity stage might have contributed to emission peaks at 70 DAT. The soil $NO_3^-$-N content during the crop growing season showed a significant correlation with $N_2O$ emission ($R$ = 0.676, $P$ = 0.011). It has been reported that soil nitrate acts as a pool of $N_2O$ precursor, and senescence of older leaves and decomposition of crop

**Table I** Yield and yield attributing parameters of rice varieties and seasonal integrated nitrous oxide emission flux ($E_{sf}$) Values within the same column followed by same letter do not differ at $P < 0.05$ level by Duncan's multiple range test

| Rice varieties/Parameters | Panicle square meter$^{-1}$ | Panicle length (cm) | Sterility (%) | Thousand grain weight (gm) | Yield (q ha$^{-1}$) | $E_{sf}$ (mg $N_2O$-N m$^{-2}$) |
|---|---|---|---|---|---|---|
| Luit | 244 66 b | 21 77 b | 8 07 d | 23 19 a | 28 10 b | 99 97 c |
| Disang | 243 00 b | 20 65 c | 7 65 e | 23 02 b | 29 04 a | 77 14 e |
| Kapilli | 245 00 b | 20 83 c | 8 43 c | 22 87 b | 27 01 c | 84 68 d |
| Siana | 250 33 a | 20 54 c | 9 33 b | 20 78 c | 26 47 d | 139 19 b |
| Phorma | 253 00 a | 22 81 a | 10 87 a | 20 12 d | 25 84 e | 150 30 a |

**Table II.** Variations in leaf area and shoot dry weight within rice varieties compared by two-way ANOVA *** = $P < 0.001$ The mean values within the column and row followed by same letter do not differ at $P < 0.05$ level by Duncan's multiple range test

| Varieties/Days after transplanting | Leaf area (cm$^2$ hill$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Luit | Disang | Kapilli | Siana | Phorma | Mean |
| 7 | 15 13 | 30 74 | 37 24 | 56 59 | 36 45 | 35 23 j |
| 14 | 97 11 | 101 78 | 113 60 | 68 49 | 48 29 | 85 85 i |
| 21 | 135 31 | 141 87 | 187 25 | 116 97 | 91 85 | 134 65 h |
| 28 | 238 37 | 249 27 | 273 07 | 283 51 | 306 25 | 270 09 g |
| 35 | 574 36 | 583 08 | 620 39 | 631 71 | 654 55 | 612 82 e |
| 42 | 647 49 | 826 00 | 798 64 | 814 92 | 894 93 | 796 40 b |
| 49 | 695 34 | 860 13 | 805 43 | 877 59 | 921 27 | 831 95 a |
| 56 | 702 25 | 820 19 | 875 10 | 892 95 | 929 52 | 844 00 a |
| 63 | 530 55 | 597 94 | 665 56 | 709 80 | 832 94 | 667 36 c |
| 70 | 500 46 | 524 07 | 645 67 | 696 44 | 800 60 | 633 45 d |
| 77 | 343 10 | 397 83 | 420 23 | 491 41 | 570 60 | 444 63 f |
| Mean | 407 22 e | 466 63 d | 494 74 c | 512 76 b | 553 39 a | |
| | | S Ed ± | LSD (0 05) | | | |
| Varieties (V) | | 6 15 | 12 20*** | | | |
| Days after transplanting (DAT) | | 9 12 | 18 10*** | | | |
| V×DAT | | 20 40 | 40 47*** | | | |
| Varieties/ Days after transplanting | Shoot dry weight (g hill$^{-1}$) | | | | | |
| | Luit | Disang | Kapilli | Siana | Phorma | Mean |
| 7 | 0 29 | 0 27 | 0 26 | 0 22 | 0 15 | 0 24 j |
| 14 | 0 90 | 0 81 | 1 09 | 0 87 | 0 76 | 0 89 i |
| 21 | 1 53 | 1 47 | 1 66 | 1 38 | 1 28 | 1 46 h |
| 28 | 5 95 | 5 92 | 7 51 | 7 60 | 8 43 | 7 08 g |
| 35 | 7 51 | 7 82 | 8 91 | 9 74 | 10 59 | 8 91 f |
| 42 | 16 25 | 15 80 | 16 63 | 16 53 | 16 59 | 16 36 e |
| 49 | 25 45 | 25 17 | 25 62 | 28 95 | 31 29 | 27 30 d |
| 56 | 26 27 | 27 09 | 27 68 | 30 32 | 31 46 | 28 57 c |
| 63 | 30 19 | 29 06 | 30 35 | 31 71 | 33 28 | 30 92 b |
| 70 | 32 63 | 32 10 | 32 39 | 33 94 | 35 71 | 33 36 a |
| 77 | 33 03 | 32 54 | 32 65 | 34 39 | 35 66 | 33 65 a |
| Mean | 16 36 d | 16 18 e | 16 80 c | 17 79 b | 18 66 a | |
| | | S Ed ± | LSD (0 05) | | | |
| Varieties (V) | | 0 16 | 0 32*** | | | |
| Days after transplanting (DAT) | | 0 24 | 0 47*** | | | |
| V×DAT | | 0 53 | 1 06*** | | | |

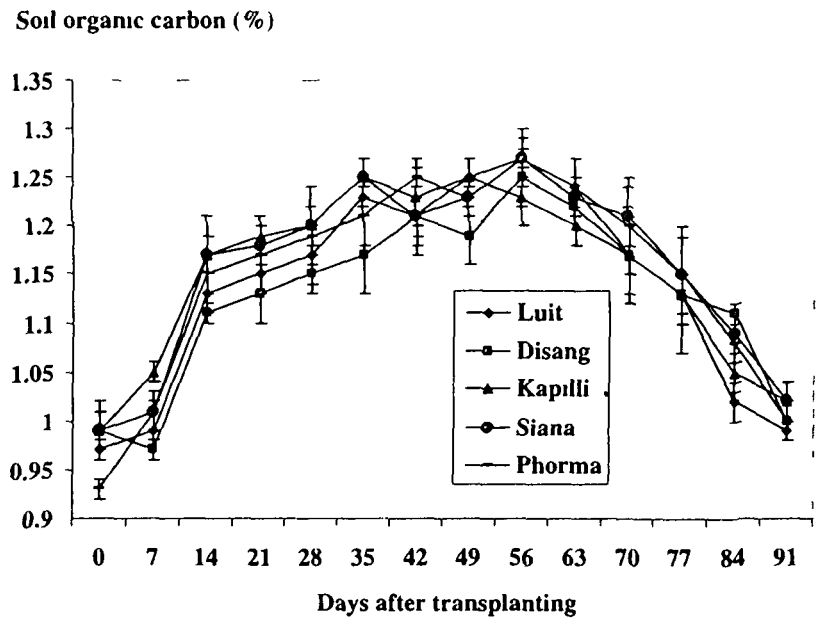


**Figure 4** Soil organic carbon content in 0–15 cm soil layer in rice field Vertical bars represent standard error of three replications

roots provides an organic N source for $N_2O$ production in the rhizosphere (Majumdar et al , 2002, Yang and Cai, 2005) *Increasing root length also helps the nitrification process by supplying* sufficient $O_2$ to the rhizosphere and thereby increasing the $NO_3^-$ content in the rice rhizosphere (Pathak, 1999) It was reported that plants can serve as a conduit for dissolved gases from the root zone to the atmosphere, and nitrous oxide as a water-soluble molecule can hence be taken up by plant roots and transported to leaves via the transpiration stream (Yan et al , 2000) The higher seasonal emission in the rice varieties Phorma and Siana with higher root biomass observed in our study might be contributed by the greater root surface area for gas transportation Soil temperature during the crop growing season ranged from 25 °C to 38 °C The recorded soil pH ranged from 5 00 to 6 40 We did not find significant correlation of soil temperature ($R$ = −0 149, $P$ = 0 331) and soil pH ($R$ = 0 252, $P$ = 0 227) with $N_2O$ emission (data not shown)

The increasing $N_2O$ flux observed after crop harvest may be due to organic matter derived from dead and decomposed roots left in soil It has been reported that the main C inputs into soil are of plant origin These C compounds can enter soil directly from above-ground and below-ground sources (Michalzik et al , 2001) In many agricultural systems where the above-ground portion of the crop is removed, the dominant C inputs to the soil will be from root turnover and exudates (Jones et al , 2004) All this organic matter significantly influences the soil microbial nitrification and denitrification, and hence $N_2O$ emission

Table I shows the differences in yield and yield attributing characteristics of the rice varieties Differences in yield attributing parameters among rice varieties were found to be significant The varieties (Phorma and Siana) with higher seasonal integrated nitrous oxide emission flux have recorded lower grain yield Disang, Luit and Kapilli, with low $N_2O$ emission, showed higher productivity in terms of grain yield

The total variance explained by factors is indicated in Table V Three factors were extracted explaining a total of 88 40% variation, which have eigenvalues greater than one A principal factor matrix after Varimax rotation for these 3 factors is given in Table VI The values in the table indicate the contribution of each variable to the factors For the purpose of interpretation only those factor loadings greater than 0 8 were considered important and these values are highlighted in bold in Table VI Factor 1 accounted for about 65 30% of the variation The variables, soil $NO_3^-$-N, leaf area, root length, root dry weight and shoot dry weight have high loadings on factor 1 and are positively associated Field water level is also highly loaded but it is negatively correlated with factor 1 and with other variables Factor 1 can be regarded as an "emission factor" since it included several variables which were found to be significantly related to $N_2O$ emission Among the variables root dry weight followed by soil $NO_3^-$-N, shoot dry weight and field water level have very high factor loadings (more than 0 95) and hence are considered to be strongly associated with nitrous oxide emission, i e factor 1 Factor 2 accounts for 11 98% of the variation and is regarded as a "soil reaction factor" since soil pH is found to be highly loaded on this factor Soil temperature is highly loaded on factor 3, which accounts for 11 10% of the variation and is regarded as a "soil physical factor" Soil temperature is highly loaded on factor 3, which accounts for 11 29% of the variation and is regarded as a "soil physical factor" Although soil pH and soil temperatures are strongly loaded on factor 2 and factor 3, respectively, the association between pH and soil temperature with other variables in factors 2 and 3 is not significant

**Table III.** Variations in root length and root dry weight within rice varieties compared by two way ANOVA *** = $P < 0.001$ NS = Non significant The mean values within the column and row followed by same letter do not differ at $P < 0.05$ level by Duncan's multiple range test

| Varieties/Days after transplanting | Root length (cm) | | | | | |
|---|---|---|---|---|---|---|
| | Luit | Disang | Kapilli | Siana | Phorma | Mean |
| 7 | 145 05 | 175 83 | 241 60 | 217 39 | 128 31 | 181 64 i |
| 14 | 184 90 | 219 96 | 368 44 | 363 88 | 158 09 | 259 05 h |
| 21 | 215 82 | 253 13 | 406 07 | 383 63 | 191 97 | 290 12 g |
| 28 | 269 37 | 312 82 | 429 91 | 439 72 | 457 24 | 381 81 f |
| 35 | 886 99 | 915 18 | 974 22 | 995 06 | 1006 48 | 955 59 d |
| 42 | 975 69 | 1006 71 | 1112 75 | 1136 41 | 1147 13 | 1075 74 c |
| 49 | 1016 11 | 1030 44 | 1111 37 | 1189 83 | 1193 96 | 1108 34 b |
| 56 | 1045 31 | 1050 43 | 1171 57 | 1170 38 | 1208 65 | 1129 27 b |
| 63 | 1066 79 | 1112 39 | 1088 02 | 1264 98 | 1284 56 | 1163 35 a |
| 70 | 982 13 | 1001 92 | 1048 90 | 1157 70 | 1177 63 | 1073 66 c |
| 77 | 799 60 | 822 06 | 877 70 | 953 93 | 983 19 | 887 30 e |
| Mean | 689 80 e | 718 26 d | 802 78 c | 842 99 a | 812 47 b | |
| | | S Ed ± | LSD (0 05) | | | |
| Varieties (V) | | 8 03 | 15 93*** | | | |
| Days after transplanting (DAT) | | 11 91 | 23 64*** | | | |
| V×DAT | | 26 64 | 52 85*** | | | |

| Varieties/Days after transplanting | Root dry weight (g hill$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Luit | Disang | Kapilli | Siana | Phorma | Mean |
| 7 | 0 11 | 0 13 | 0 17 | 0 14 | 0 04 | 0 12 h |
| 14 | 0 31 | 0 34 | 0 40 | 0 37 | 0 26 | 0 34 g |
| 21 | 0 64 | 0 67 | 0 77 | 0 57 | 0 51 | 0 63 f |
| 28 | 1 01 | 1 06 | 1 13 | 1 47 | 1 59 | 1 25 e |
| 35 | 2 41 | 2 58 | 2 64 | 2 82 | 2 93 | 2 68 d |
| 42 | 2 95 | 3 05 | 3 54 | 3 73 | 3 85 | 3 42 c |
| 49 | 3 74 | 3 87 | 3 87 | 3 92 | 4 12 | 3 90 a |
| 56 | 3 85 | 4 23 | 4 08 | 4 13 | 4 22 | 4 10 a |
| 63 | 3 89 | 3 92 | 4 18 | 4 10 | 4 23 | 4 07 a |
| 70 | 3 63 | 3 85 | 4 08 | 3 97 | 4 12 | 3 93 a |
| 77 | 3 56 | 3 46 | 3 57 | 3 71 | 3 82 | 3 63 b |
| Mean | 2 37 c | 2 47 bc | 2 58 ab | 2 63 a | 2 70 d | |
| | | S Ed ± | LSD (0 05) | | | |
| Varieties (V) | | 0 06 | 0 13*** | | | |
| Days after transplanting (DAT) | | 0 09 | 0 19*** | | | |
| V×DAT | | 0 21 | 0 42$^{NS}$ | | | |

## 4. CONCLUSIONS

The experiment on $N_2O$ emission from a rainfed rice ecosystem revealed that wide fluctuations exist in $N_2O$ emission rates among different rice varieties in relation to soil and plant properties The plant and soil variables such as root dry weight, soil nitrate-N, shoot dry weight, root length, leaf area and field water show a significant relationship with $N_2O$ emission Among these variables, root dry weight, soil $NO_3^-$-N, shoot dry weight and field water level have very high factor loadings and therefore are identified as main driving properties influencing $N_2O$ emission High seasonal $N_2O$-emitting varieties with profuse vegetative growth showed low yield potential Based on these observations it can be suggested that a biological mitigation strategy can be developed if suitable rice genotypes are selected on the basis of plant growth parameters, soil properties, emission characteristics and yield potential Low $N_2O$-emitting varieties from a similar agroecosystem can be used by plant breeders in variety improvement programs to develop low greenhouse gas-emitting varieties The important plant and soil factors associated with $N_2O$ emissions identified in the present study may help in the understanding of the mechanisms of $N_2O$ transport and regulations into the atmosphere Based on this study the rice varieties Disang, Luit and

**Table IV** Variations in soil $NO_3^-$-N content of experimental field within rice varieties compared by two way ANOVA *** = $P < 0.001$ The mean values within the column and row followed by same letter do not differ at $P < 0.05$ level by Duncan's multiple range test

| Varieties/Days after transplanting | Soil $NO_3^-$ N (Kg $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Luit | Disang | Kapilli | Siana | Phonna | Mean |
| 0 | 20 10 | 20 88 | 20 50 | 20 90 | 20 80 | 20 64 l |
| 7 | 23 70 | 22 40 | 22 50 | 21 50 | 20 61 | 22 14 i |
| 14 | 21 90 | 21 70 | 21 60 | 20 50 | 21 80 | 21 50 j |
| 21 | 20 50 | 21 80 | 20 80 | 20 01 | 21 30 | 20 88 k |
| 28 | 19 76 | 20 46 | 20 56 | 21 50 | 21 13 | 20 68 l |
| 35 | 30 40 | 30 20 | 30 53 | 30 86 | 30 83 | 30 56 g |
| 42 | 28 50 | 28 04 | 28 00 | 28 70 | 28 30 | 28 31 h |
| 49 | 34 80 | 34 10 | 34 11 | 34 00 | 34 80 | 34 36 b |
| 56 | 30 50 | 31 30 | 32 50 | 32 80 | 33 10 | 32 04 e |
| 63 | 31 00 | 30 50 | 29 70 | 30 10 | 32 40 | 30 74 f |
| 70 | 33 10 | 34 00 | 34 10 | 34 80 | 35 00 | 34 20 c |
| 77 | 32 60 | 32 80 | 33 00 | 34 50 | 34 30 | 33 44 d |
| 74 | 34 00 | 34 90 | 34 70 | 35 40 | 34 00 | 34 60 a |
| 91 | 33 90 | 35 01 | 34 80 | 34 20 | 34 10 | 34 40 b |
| Mean | 28 20 d | 28 44 c | 28 39 c | 28 55 b | 28 75 a | |
| | | S Ed ± | LSD (0 05) | | | |
| Varieties (V) | | 0 03*** | 0 06*** | | | |
| Days after transplanting (DAT) | | 0 05*** | 0 09*** | | | |
| V×DAT | | 0 11*** | 0 21*** | | | |

**Table V.** Total variance explained for each factor

| Component | % of variance | Cumulative % |
|---|---|---|
| 1 | 65 305 | 65 305 |
| 2 | 11 989 | 77 294 |
| 3 | 11 106 | 88 401 |
| 4 | 6 362 | 94 763 |
| 5 | 3 904 | 98 667 |
| 6 | 0 794 | 99 461 |
| 7 | 0 430 | 99 891 |
| 8 | 8 675E-02 | 99 978 |
| 9 | 2 230E-02 | 100 000 |
| 10 | 1 162E 05 | 100 000 |

**Table VI.** Principal factor matrix after varimax rotation Numbers in bold are those with factor loadings greater than 0 80

| Variables | Factor | | | Proportion of each variable's variance explained by the underlying factors |
|---|---|---|---|---|
| | 1 | 2 | 3 | |
| $N_2O$ flux | 0 646 | 0 238 | | 0 482 |
| Soil $NO_3^-$-N | **0 961** | | | 0 929 |
| Soil organic carbon | 0 643 | 0 423 | 0 482 | 0 825 |
| Field water level | **–0.966** | | | 0 943 |
| Leaf area | **0.874** | 0 446 | | 0 963 |
| Root length | **0.939** | 0 291 | | 0 967 |
| Rood dry weight | **0.977** | 0 141 | | 0 976 |
| Shoot dry weight | **0.955** | –0 143 | | 0 938 |
| Soil temperature | –0 171 | –0 150 | **0 925** | 0 908 |
| Soil pH | | **0.944** | –0 122 | 0 909 |

Kapilli, with lower $N_2O$ emission flux and high yield potential, can be considered suitable for growth in a northeastern state of India

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# Nitrous Oxide Emissions from Fields with Different Wheat and Rice Varieties*[1]

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## ABSTRACT

Plant species of cropping systems may affect nitrous oxide ($N_2O$) emissions. A field experiment was conducted to investigate dynamics of $N_2O$ emissions from rice-wheat fields from December 2006 to June 2007 and the relationship between soil and plant parameters with $N_2O$ emissions. The results indicated that $N_2O$ emissions from different wheat varieties ranged from 12 to 291 μg $N_2O$-N $m^{-2}$ $h^{-1}$ and seasonal $N_2O$ emissions ranged from 312 to 385 mg $N_2O$-N $m^{-2}$. In the rice season, it was from 11 to 154 μg $N_2O$-N $m^{-2}$ $h^{-1}$ with seasonal $N_2O$ emission of 190–216 mg $N_2O$-N $m^{-2}$. The seasonal integrated flux of $N_2O$ differed significantly among wheat and rice varieties. The wheat variety HUW 234 and rice variety Joymoti showed higher seasonal $N_2O$ emissions. In the wheat season, $N_2O$ emissions correlated with soil organic carbon (SOC), soil $NO_3^-$-N, soil temperature, shoot dry weight, and root dry weight. Among the variables assessed, soil temperature followed by SOC and soil $NO_3^-$-N were considered as the important variables influencing $N_2O$ emission. $N_2O$ emission in the rice season was significantly correlated with SOC, soil $NO_3^-$-N, soil temperature, leaf area, shoot dry weight, and root dry weight. The main driving forces influencing $N_2O$ emission in the rice season were soil $NO_3^-$-N, leaf area, and SOC.

*Key Words*: nitrous oxide emission, plant characteristics, rice field, soil factors, wheat field

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## INTRODUCTION

Nitrous oxide ($N_2O$) is an important greenhouse gas contributing to global warming. According to the International Panel on Climate Change (IPCC) 2007, it reached a concentration of 319 nL $L^{-1}$ in 2005. Globally, agricultural $N_2O$ emissions have increased by nearly 17% from 1990 to 2005, and are projected to increase by 35%–60% up to 2030 due to increased nitrogen (N) fertilizer use and increased animal manure production. $N_2O$ is produced by soil microorganisms *via* the processes of nitrification and denitrification (Davidson and Schimel, 1995). Important factors regulating emissions are fertilizer N inputs for crop production, soil temperature, soil moisture, soil nitrate ($NO_3^-$) concentrations, and the availability of organic C substrate for microorganisms (Hutchinson and Davidson, 1993). Besides, the impact of soil factors on $N_2O$ emission, and the role of growing plants in $N_2O$ production and emissions from agricultural systems have been documented (Muller, 2003; Baruah *et al.*, 2010a). It has been shown that $N_2O$ production in soil is mainly controlled by the availability of $NO_3^-$, labile C compounds, and $O_2$ (Del Grosso *et al.*, 2000), which is greatly affected by the existence of growing plants (Conrad *et al.*, 1983).

Several studies have contributed to our understanding of the role plants play in $N_2O$ emissions (Yu *et al.*, 1997). The intensity and species composition of cropping systems may affect soil $N_2O$ emissions due to the impact of plants on soil N and C cycling and soil water content (Pathak, 1999). Cultivar differences in $N_2O$ emissions are reported from a legume-cereal intercropping (Pappa *et al.*, 2011). Mosier *et al.* (1990) have indicated that the young rice plants facilitate the efflux of $N_2$ and $N_2O$ from flooded paddy soil to the

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atmosphere. Results obtained by Smart and Bloom (2001) demonstrated that wheat leaves emitted $N_2O$ during $NO_3^-$ assimilation. Zou *et al.* (2005) assessed the contribution of plants to $N_2O$ emissions in a winter wheat crop and suggested that soil-crop system $N_2O$ emissions were greatly affected by plants.

In the Asian subtropics rice-wheat production systems occupy 26 Mha of cultivated land. India alone has 10.5 Mha of cultivated land under rice-wheat cultivation. Rice is grown in three different seasons, winter, autumn, and summer, in Assam a state of northeast India. The area under summer rice and wheat has increased with enhanced availability of irrigation facilities. Although $N_2O$ emissions from agricultural fields in India have been reported (Mosier *et al.*, 1990; Aulakh *et al.*, 2001), the previous studies have not emphasised the relationship between soil and plant factors with respect to $N_2O$ emissions from rice wheat rotations. Therefore, the present investigation was carried out with the aim of studying the dynamics of $N_2O$ emissions in rice and wheat rotations to assess the influence of soil and plant factors.

## MATERIALS AND METHODS

### *Site description*

The study was conducted at Tezpur in the North Bank Plain Agro-climatic Zone of Assam (26° 41′ N, 92° 50′ E), India. The experimental site was located in a farmer's rice-wheat rotation field 6 km west of the Tezpur University campus. This zone has a subtropical climate and monsoon rainfall pattern. Winters extend from the month of October to the month of February, and are cold and generally dry. The minimum temperature in winter varies between 6 and 8 °C. Summer starts in mid May, accompanied by high humidity and rainfall. The maximum temperature varies between 35 and 38 °C. Assam experiences an average annual rainfall of 230 cm. The peak of the monsoon is during June. The soils there are acidic except the new alluvial soils, which are neutral in reaction. The major soil groups are: new and old alluvial soils, old mountain valley alluvial soils, non-lateritic red soil, and lateritic red soils. Prior to the inception of the experiment, the wheat field soil contained 370 kg $ha^{-1}$ of available N, 37 kg $ha^{-1}$ of available phosphorus (P), and 231 kg $ha^{-1}$ of available potassium (K). The recorded available N, P, and K of the rice field soil were 375, 34, and 239 kg $ha^{-1}$, respectively. Soil pH values of the wheat and rice fields were 5.4 and 5.2, respectively.

### *Experimental setup*

Seeds of wheat varieties Sonalika, HUW 468, HUW 234, and DBW 14 were sown in the well prepared field on December 27, 2006, at a row spacing of 20 cm. Each variety was replicated 3 times in a randomized block design with plot sizes of 2 m × 2 m. Fertilizers were applied at the rate of 80:34:42 kg N-$P_2O_5$-$K_2O$ $ha^{-1}$ in the forms of urea, single super phosphate, and muriate of potash. A third of the N and all the $P_2O_5$ and $K_2O$ were applied as basal doses by broadcasting prior to the last ploughing and mixed thoroughly with the soil. The remaining two third of the N was top dressed at the crown root initiation stage, *i.e.*, 25 days after sowing (DAS). One pre-sowing irrigation was applied 3 days before sowing to enable quick and uniform germination of seeds. Wheat varieties were harvested on the April 7, 2007. Three summer rice (locally known as Boro rice) varieties, Bishnuprasad, Joymoti, and Kanaklata, were sown in a nursery bed on January 10, 2007, and after ploughing, puddling, and leveling of the field the seedlings of each variety were transplanted on February 8, 2007 to plots of size 6 m × 5 m. The seedlings were manually transplanted at a density of 2 seedlings per hill at a spacing of 20 cm × 15 cm (row to row × plant to plant). Each variety was replicated 3 times in a randomized block design. Fertilizers were applied at the rate of 60:30:30 kg N-$P_2O_5$-$K_2O$ $ha^{-1}$ in the forms of urea, single super phosphate, and muriate of potash. One third of the total urea dose was applied at the time of final puddling, before transplanting along with the full dose of single super phosphate ($P_2O_5$) and muriate of potash ($K_2O$). The second and third doses of urea were top dressed 30 and 59 days after transplanting (DAT) of the crop. Rice was irrigated at the time of transplanting and 34 and 41 DAT of the crop corresponding to drop in water level in the field. Rice varieties were harvested on June 7, 2007.

### *Gas sampling and analysis*

Gas samples were collected by a closed chamber technique (Buendia *et al.*, 1997). Chambers were 50 cm long, 30 cm wide, and 70 cm tall, and made of 6 mm thick acrylic sheet. In each plot, three rectangular U-shaped aluminium channels (50 cm × 30 cm), supported on an aluminium frames (50 cm × 30 cm × 15 cm), were used to accommodate the chambers. The aluminium channels were inserted into the soil to a depth of 15 cm 7 days before sowing and transplanting of crops. Six hills of rice plants (two seedlings per

hill) were enclosed inside each channel. The aluminium trays were filled with water to a depth of 2.5 cm during gas sampling, which acted as an air seal when the chambers were placed on the tray. A battery-operated fan was fixed inside each chamber to homogenize the air. The temperature inside the chamber was recorded at the time of sample collection using a thermometer which was fixed on the inside wall of the chamber for the calculation of box volume at STP. The gas samples were drawn with the help of a 50 mL airtight syringe fitted with a three-way tap cork at fixed intervals of 0, 15, 30, and 45 min, once in the morning at 09:00 and again in the afternoon at 14:00. The gas samples in the wheat plant were collected at 11 DAS (at seedling establishment) onwards at weekly intervals until 2 weeks after harvest. Soil and plant parameters were recorded at the time of gas sampling. The gas samples in the rice plant were collected from the day of transplanting onwards at weekly intervals until 3 weeks after harvest and the soil and plant parameters were also recorded at the time of gas sampling.

The gas samples were brought to the laboratory and analysed for $N_2O$ fluxes, using a Varian model 3 800 gas chromatograph (USA) fitted with an electron capture detector (ECD) and a stainless steel Chromopack capillary column (50 cm long, 0.53 mm outside diameter, 1 μm inside diameter). The operating temperature of the column, injector and detector were 80 °C, 200 °C, and 300 °C, respectively. $N_2O$ fluxes were calculated according to the methods of Parashar *et al.* (1996). The average of morning and afternoon fluxes were considered as the flux value for the day and expressed as μg $N_2O$-N $m^{-2}$ $h^{-1}$. Cumulative $N_2O$ emissions for the entire crop growth period were computed by the method given by Naser *et al.* (2007) and expressed as seasonal integrated fluxes ($E_{sif}$) in mg $N_2O$-N $m^{-2}$.

*Soil and plant sample analysis*

Soil samples were randomly collected from wheat and rice growing fields (20 different spots) from a depth of 15 cm before sowing and transplanting of the crops. For weekly soil analysis during crop growth, samples were taken from between the crop rows from each plot using a core sampler. Samples collected from different spots were thoroughly mixed to make one composite sample. Composite soil samples were air-dried under shade, ground, and passed through a 2-mm sieve. The sieved soil samples were stored in polythene bags until analysis. The soil moisture was determined gravimetrically. Available N, available P, and available K were determined using the Kjeldahl method, Bray's I method, and flame photometric method, respectively, as described by Jackson (1973). Soil organic carbon (SOC) was determined using the wet digestion method of Walkley and Black (1947). Soil pH (1:2.5 soil-water ratios) was measured using a Systronics Griph model D pH meter. Soil temperature was measured at 5 cm soil depth with a soil thermometer. Soil $NO_3^-$-N was determined by the method of Ghosh *et al.* 1983. Standing water levels of the experimental field were recorded at weekly intervals during gas sampling. Plant samples from each replication were uprooted and washed thoroughly with water, and root and shoots were separated and dried at 75 ± 2 °C in an oven until a constant weight was observed and weighed. Leaf area was measured using a portable laser leaf area meter (Model CI-203, CID Inc., USA). Rice yield was determined from the total plot area by harvesting all the hills excluding the hills bordering the plots. After threshing the grain yield obtained from each plot was weighed in kg $plot^{-1}$ and then converted to t $ha^{-1}$.

*Statistical analysis*

Statistical analyses of the data were performed using the SPSS 11.5 software package with differences in the parameters, among the rice and wheat varieties, analysed by one-way analysis of variance (ANOVA) and subsequently by Duncans's multiple range test. Correlations between $N_2O$ fluxes and means of other plant and soil variables were determined by factor analysis. The factor loadings, the percentage variability explained by each factor, and the communalities for each variable were determined.

## RESULTS AND DISCUSSION

*Emissions of nitrous oxide in the wheat season*

Nitrous oxide emissions during the rainfed wheat growing season varied from 12 to 291 μg $N_2O$-N $m^{-2}$ $h^{-1}$ (Fig. 1). The emission rate increased gradually from 18 DAS onwards. At 39 DAS, $N_2O$ flux of 273 μg $N_2O$-N $m^{-2}$ $h^{-1}$ were observed for HUW 234, followed by 267, 233, and 222 μg $N_2O$-N $m^{-2}$ $h^{-1}$ recorded for DBW 14, HUW 468, and Sonalika, being significantly different among the verities ($P < 0.05$). Emissions decreased considerably during the period from 46 to 67 DAS. The mean $N_2O$ emissions from 46 to 67 DAS were 86, 95, 109, and 110 μg $N_2O$-N $m^{-2}$ $h^{-1}$ for Sonalika,

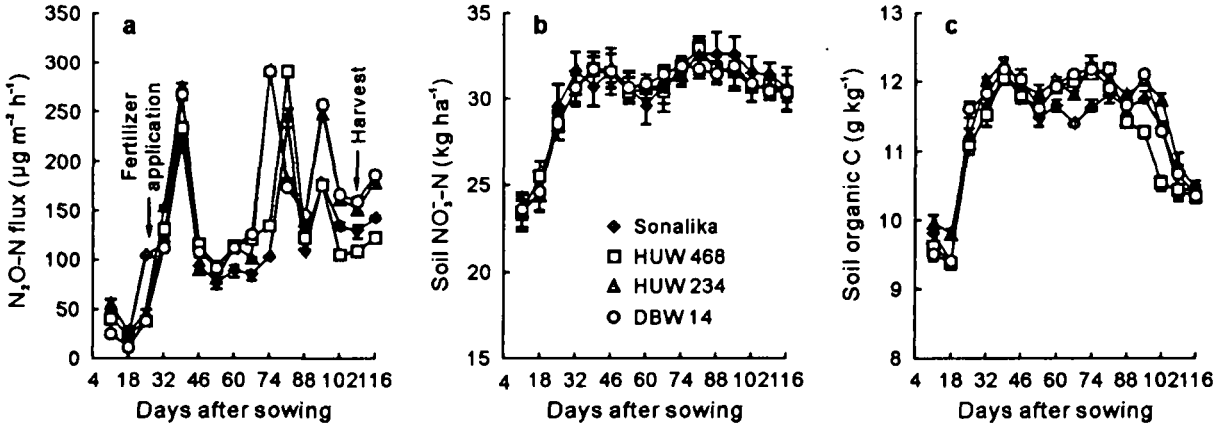


Fig. 1 Variations in nitrous oxide flux (a), soil $NO_3^-$-N (b), and soil organic carbon (c) in the wheat season. Vertical bars represent standard errors of three replications. The arrows indicate the time of fertilizer application and harvest.

HUW 234, DBW 14, and HUW 468, respectively. The rate of emission increased sharply after panicle initiation and at crop ripening stage and declined at harvest. During this period, emission peaks were observed at 74, 81, and 94 DAS. The average emission rates from 74 to 102 DAS for Sonalika, HUW 468, HUW 234, and DBW 14 were 153, 165, 204, and 206 μg $N_2O$-N $m^{-2}$ $h^{-1}$, respectively. The increment in $N_2O$ emission in the early growth period observed in our study was probably due to increased SOC of the experimental field (Fig. 1). The availability of SOC is considered to be a major factor influencing nitrification and denitrification reactions which simultaneously occur in aerobic and anaerobic microsites of soil aggregates (Smith, 1990). The emission peaks at 39 and 74 DAS were attributed to increased availability of substrates for nitrification and denitrification reactions contributed by hydrolysis of urea applied at the crown root initiation stage. Studies have shown increases in soil $N_2O$ emissions following N fertilizer application (Aulakh *et al.*, 2001; Baruah *et al.*, 2010b) and it has also been stated that $N_2O$ emission remains high for several weeks before returning to background levels following fertilization (Conrad *et al.*, 1983). Our results showing emission peaks at 39 and 74 DAS are in agreement with these findings. Increased concentrations of soil $NO_3^-$-N might have contributed to higher emission rates after panicle initiation and at crop ripening stage (Fig. 1). Cumulative $N_2O$ emissions for the entire crop growth period differed significantly among varieties at $P < 0.05$ level by Duncan's multiple range test (Table I). Higher seasonal $N_2O$ emission ($E_{sif}$) of 384 mg $N_2O$-N $m^{-2}$ was recorded for the wheat variety HUW 234.

TABLE I

Seasonal integrated flux ($E_{sif}$) values of $N_2O$ and yields of wheat and rice varieties

| Crop | Variety | $E_{sif}$ | Yield |
|---|---|---|---|
| | | mg $N_2O$-N $m^{-2}$ | t $ha^{-1}$ |
| Wheat | Sonalika | 312±0.62[a)] d[b)] | 3.0±0.03 b |
| | HUW 468 | 339±0.67 c | 2.7±0.04 d |
| | HUW 234 | 385±0.52 a | 2.8±0.04 c |
| | DBW 14 | 382±0.61 b | 3.1±0.06 a |
| Rice | Bishnuprasad | 206±0.62 b | 3.3±0.07 b |
| | Joymoti | 216±0.60 a | 3.2±0.02 c |
| | Kanaklata | 190±0.57 c | 3.3±0.05 a |

[a)]Mean±standard deviation.
[b)]Values followed by the same letter(s) are not significantly different at $P < 0.05$ level by Duncan's multiple range test.

*Emissions of nitrous oxide in the rice season*

Nitrous oxide emissions in the rice season ranged from 11 to 154 μg $N_2O$-N $m^{-2}$ $h^{-1}$ (Fig. 2). All the three rice varieties showed similar patterns of $N_2O$ emissions. The average $N_2O$ flux at transplanting (0 DAT) was 19 μg $N_2O$-N $m^{-2}$ $h^{-1}$. From 7 DAT onwards, the rate of emission gradually increased and at 35 DAT, $N_2O$ flux peaks of 123 and 110 μg $N_2O$-N $m^{-2}$ $h^{-1}$ were observed for Joymoti and Kanaklata, respectively. For Bishnuprasad, an emission peak of 121 μg $N_2O$-N $m^{-2}$ $h^{-1}$ was recorded at 42 DAT. The second emission peaks were recorded at 63 DAT for Joymoti and at 70 DAT for Kanaklata and Bishnuprasad. The third emission peaks were recorded at 112 DAT for all the rice varieties. High soil $NO_3^-$-N due to applied urea at the time of transplanting and further reduction of nitrate under anaerobic soil due to the high water level

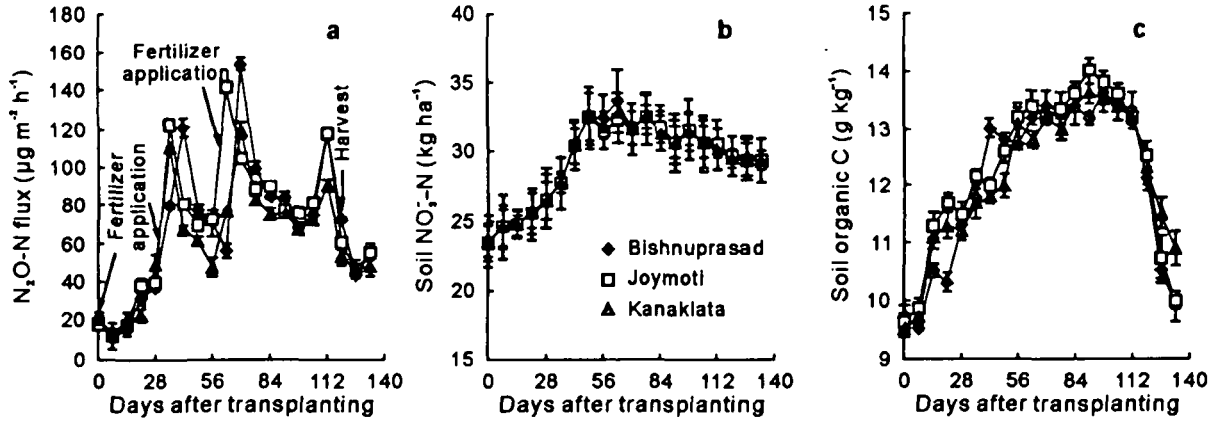


Fig. 2 Variations in nitrous oxide flux (a), soil $NO_3^-$-N (b), and soil organic carbon (c) in the rice season. Vertical bars represent standard errors of three replications. The arrows indicate the time of fertilizer application and harvest.

(2.8–4.1 cm) of the experimental field contributed to the increasing rate of $N_2O$ emission from 7 DAT onwards. The observed emission peaks at 35 and 42 DAT may be attributed by top dressing of nitrogenous fertilizer urea at 30 DAT. It was reported that application of inorganic nitrogen promotes both nitrification and denitrification processes by providing substrates for nitrifying and denitrifying microorganisms (Steinbach and Alvarez, 2006). The emission peaks at 63 and 70 DAT were also attributed to increased soil $NO_3^-$-N as a result of nitrogen fertilizer top dressing at 59 DAT. The further decrease in $N_2O$ emissions from 77 to 98 DAT may have been due to decreased substrate availability for denitrifying and nitrifying microorganisms. The higher rate of emission at 112 DAT was attributed to high substrate availability for $N_2O$ production in rice rhizosphere as a result of decomposition of leaf litter and roots as suggested by Yang and Cai (2005). $E_{sif}$ recorded for the rice varieties showed significant differences ($P < 0.05$), with higher emissions for the rice variety Joymoti (Table I)

*Relationship of SOC, soil $NO_3^-$-N, and soil temperature with $N_2O$ emissions in the rice and wheat seasons*

The SOC content during the wheat growing season varied from 9.3 to 12.3 g kg$^{-1}$ (Fig. 1). The recorded SOC during the rice growing season varied from 9.5 to 14.0 g kg$^{-1}$ (Fig. 2). In both the seasons, the increase in SOC was recorded during the flowering and ripening stages. The increase in SOC was attributed to root exudation resulting from increasing root biomass at these stages (Table II). It has been reported that the dissolved organic carbon (DOC) in the rhizosphere of rice plants is controlled by release of organic materials from roots, which increased significantly with plant growth (Lu *et al.*, 2000). With the increase in decomposition of plant residues in soil, DOC is reported to increase with simultaneous increases in $N_2O$ emission (Huang *et al.*, 2004). The amount of DOC between rice flowering and maturation increases because the root exudation from rice plants reaches the maximum at these stages (Holzapfel-Pschorn *et al.*, 1986; Aulakh *et al.*, 2001). We observed significant correlations of $N_2O$ emissions from both wheat and rice seasons with SOC (Figs. 3 and 4). In the wheat season, soil $NO_3^-$-N content increased from 25 to 46 DAS and again from 74 to 95 DAS, it showed an increasing trend (Fig. 1). In the rice season, soil $NO_3^-$-N increased from 14 DAT onwards, with the maximum recorded at 63 DAT (Fig. 2). We observed significant correlations of soil $NO_3^-$-N with $N_2O$ emissions in the wheat and rice seasons (Figs. 3 and 4). Soil temperature of the experimental field during the wheat growing season ranged from 17.3 to 29.0 °C, whereas during the rice growing season soil temperature ranged from 16.0 to 31.0 °C. $N_2O$ emissions showed significant relationships with soil temperature in the wheat and rice seasons (Figs. 3 and 4). Soil temperature is a key variable that affects the emission rates of $N_2O$. Emissions increased with increasing soil temperature due to the fact that rates of enzymatic processes generally increased with temperature as long as other factors were not limiting. A rise in temperature also affects soil respiration and anaerobicity thus influences denitrification rates and $N_2O$ emissions (Smith, 1997).

*Plant physiological parameters and $N_2O$ emissions in the rice and wheat seasons*

Leaf area in all the varieties increased up to the grain-filling stage and declined thereafter. Among the

TABLE II

Variations in leaf area, shoot dry weight, and root dry weight within rice varieties compared by one-way ANOVA

| Rice variety | Growth stage | | | | |
|---|---|---|---|---|---|
| | Seedling (7 DAT[a]) | Early tillering (28 DAT) | Maximum tillering (56 DAT) | Panicle emergence (70 DAT) | Ripening (84 DAT) |
| | | | *Leaf area ($cm^2$ $hill^{-1}$)*[b] | | |
| Bishnuprashad | 48.88 a[c] | 312.33 a | 607.15 b | 794.05 b | 762.63 b |
| Joymoti | 49.62 a | 318.87 a | 645.51 a | 866.63 a | 831.28 a |
| Kanaklata | 50.27 a | 319.25 a | 585.21 c | 759.85 c | 771.64 b |
| Standard deviation | 0.99 | 2.76 | 3.89 | 1.60 | 4.29 |
| LSD (0.05)[d] | 2.75 | 7.67 | 10.80 | 4.45 | 11.91 |
| | | | *Shoot dry weight (g $hill^{-1}$)* | | |
| Bishnuprashad | 0.29 a | 1.48 a | 7.62 b | 19.74 c | 27.32 b |
| Joymoti | 0.32 a | 1.52 a | 17.00 a | 29.50 a | 35.10 a |
| Kanaklata | 0.26 a | 1.35 a | 7.21 b | 20.84 b | 26.31 b |
| Standard deviation | 0.04 | 0.08 | 0.36 | 0.22 | 0.64 |
| LSD (0.05) | 0.11 | 0.23 | 1.01 | 0.62 | 1.76 |
| | | | *Root dry weight (g $hill^{-1}$)* | | |
| Bishnuprashad | 0.09 a | 0.43 b | 2.13 b | 3.66 a | 4.15 a |
| Joymoti | 0.06 a | 0.56 a | 2.48 a | 3.81 a | 4.36 a |
| Kanaklata | 0.10 a | 0.45 b | 1.48 c | 3.00 a | 3.32 b |
| Standard deviation | 0.02 | 0.04 | 0.10 | 0.38 | 0.15 |
| LSD (0.05) | 0.06 | 0.10 | 0.27 | 1.06 | 0.41 |

[a]Days after transplanting; [b]Hill means a hole where the seedlings are planted in the muddy soil.
[c]Values followed by the same letter(s) are not significantly different at $P < 0.05$ level by Duncan's multiple range test.
[d]Least significant difference at the 0.05 level.

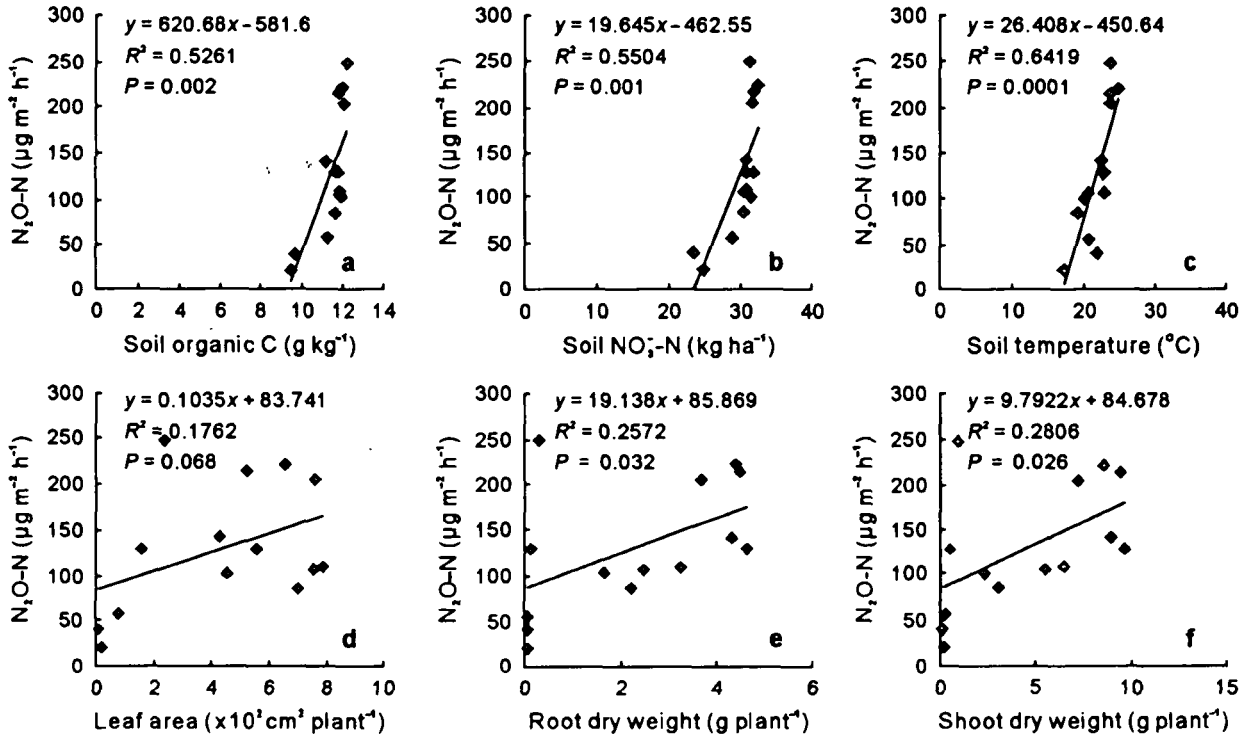


Fig. 3 Correlations of $N_2O$ emissions with soil organic carbon (a), soil $NO_3^-$-N (b), soil temperature (c), leaf area (d), root dry weight (e), and the shoot dry weight in the wheat season.

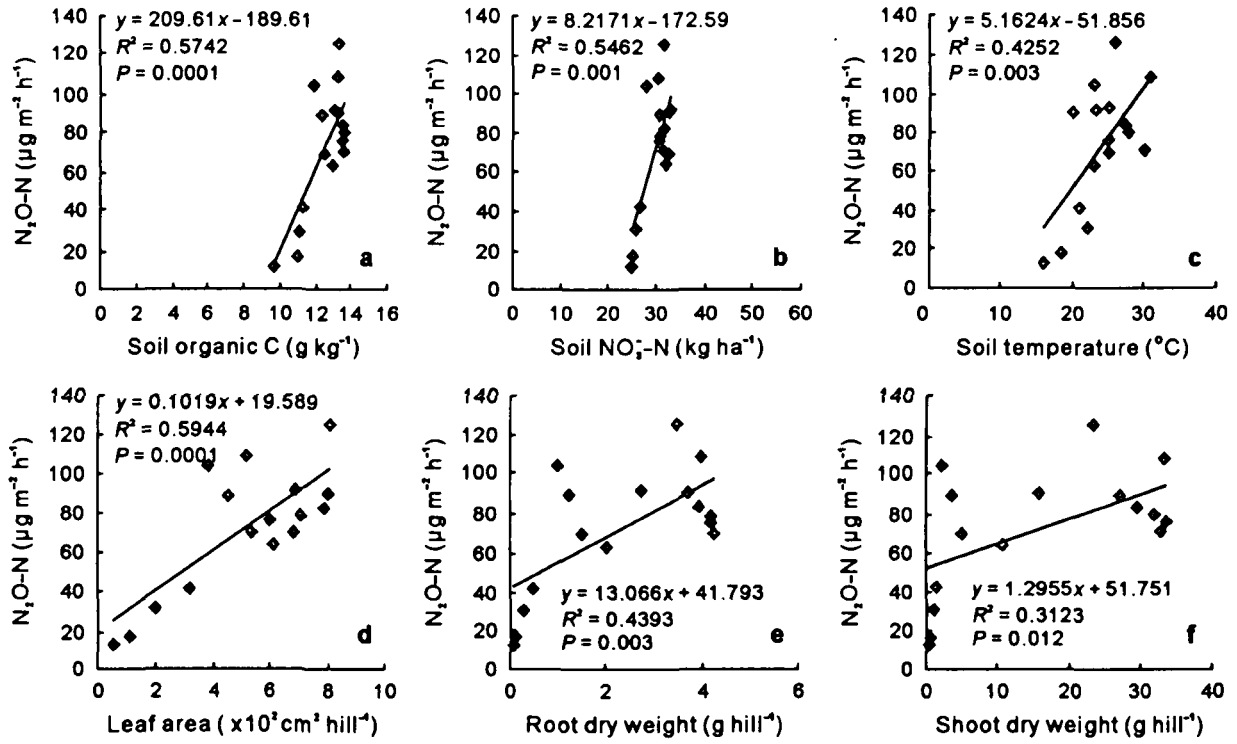


Fig. 4 Correlations of $N_2O$ emissions with soil organic carbon (a), soil $NO_3^-$-N (b), soil temperature (c), leaf area (d), root dry weight (e), and shoot dry weight in the rice season.

the wheat varieties, significantly higher ($P < 0.05$) growth in terms of leaf area extension and root and shoot dry weight accumulation was recorded in HUW 234, which also exhibited significantly higher ($P < 0.05$) seasonal $N_2O$ emissions (Table III). Among the rice varieties, Joymoti showed higher leaf area, root dry weight, and shoot dry weight (Table II) and higher seasonal $N_2O$ emissions compared to Bishnuprasad and Kanaklata (Table I). We observed significant correlations of leaf area, root dry weight, and shoot dry weight with $N_2O$ emissions in the rice season (Fig. 4). In the wheat season, $N_2O$ emissions showed significant correlations with root dry weight and shoot dry weight. However, leaf area did not reveal a significant relationship with $N_2O$ emission (Fig. 3). It has been reported that rice plants act as an effective pathway for $N_2O$ transport through aerenchyma cells in submerged soils (Xu *et al.*, 2001) and during day time, transport of $N_2O$ from roots to shoots is reported to take place within the transpiration stream and release through open stomata (Ferch and Römheld, 2001). A similar mechanism of emission might be the reason for the observed correlation of $N_2O$ emission with leaf area in the present study. Studies have demonstrated the correlation between $N_2O$ emissions from plants and plant respiratory coefficients and indicated that plant-mediated $N_2O$ emissions might be associated with plant respiration (Zou *et al.*, 2005). Hakata *et al.* (2003) studied variations in $N_2O$ emission in 17 plant taxa and suggested that plant $N_2O$ emissions might be involved with intrinsic physiological characteristics.

Rice and wheat varieties with more root biomass had higher emissions of $N_2O$, possibly because of great surface area for diffusion of these gases into roots. Significant variations in the yield potential of wheat and rice varieties were observed (Table I). Maximum yield was recorded from the wheat variety DBW 14 and rice variety Kanaklata. The total variance explained by factors was indicated in Table IV. The loadings indicated the contribution of each variable to the factors. The factor loadings greater than 0.70 were considered important. For wheat, three factors with eigenvalues > 1 were extracted. Factors 1, 2, and 3 accounted for about 59.97%, 19.84%, and 13.13%, respectively, of total variance explained. The variables, leaf area, root dry weight, and shoot dry weight, showed high loadings in factor 1 and were positively associated. In factor 2, the parameters with greatest positive weight were $N_2O$ flux, soil temperature, soil organic carbon, and soil $NO_3^-$-N. A significant positive interrelationship be-

TABLE III

Variations in leaf area, shoot dry weight, and root dry weight within wheat varieties

| Wheat variety | Growth stage | | | | |
|---|---|---|---|---|---|
| | Seedling (11 DAS[a]) | Crown root initiation (25 DAS) | Active vegetative (53 DAS) | Panicle emergence (67 DAS) | Ripening (81 DAS) |
| | | | *Leaf area ($cm^2$ $plant^{-1}$)* | | |
| Sonalika | 7.73 a[b] | 69.14 c | 685.08 c | 778.22 b | 640.00 c |
| HUW 468 | 9.33 a | 73.27 b | 656.00 d | 767.27 b | 612.16 d |
| HUW 234 | 8.50 a | 96.66 a | 741.26 a | 799.25 a | 691.30 a |
| DBW 14 | 7.57 a | 74.22 b | 712.14 b | 793.15 a | 670.13 b |
| Standard deviation | 0.84 | 0.54 | 2.20 | 4.66 | 3.20 |
| LSD (0.05) | 2.05 | 1.33 | 5.37 | 11.41 | 7.84 |
| | | | *Shoot dry weight (g $plant^{-1}$)* | | |
| Sonalika | 0.12 b | 0.23 b | 2.29 c | 6.79 a | 8.41 b |
| HUW 468 | 0.16 ab | 0.27 a | 2.29 c | 6.12 b | 7.86 c |
| HUW 234 | 0.14 ab | 0.27 a | 3.16 b | 6.83 a | 9.49 a |
| DBW 14 | 0.17 a | 0.27 a | 4.50 a | 6.20 b | 8.50 b |
| Standard deviation | 0.02 | 0.01 | 0.03 | 0.12 | 0.20 |
| LSD (0.05)[c] | 0.04 | 0.03 | 0.07 | 0.29 | 0.48 |
| | | | *Root dry weight (g $plant^{-1}$)* | | |
| Sonalika | 0.05 b | 0.07 c | 1.98 c | 3.10 ab | 4.27 ab |
| HUW 468 | 0.04 b | 0.06 d | 2.09 b | 2.82 b | 4.08 b |
| HUW 234 | 0.05 b | 0.09 a | 2.58 a | 3.63 a | 4.87 a |
| DBW 14 | 0.07 a | 0.08 b | 2.08 b | 3.36 ab | 4.35 ab |
| Standard deviation | 0.00 | 0.00 | 0.45 | 0.29 | 0.27 |
| LSD (0.05) | 0.01 | 0.01 | 1.10 | 0.71 | 0.65 |

[a] Days after sowing.

[b] Values followed by the same letter(s) are not significantly different at $P < 0.05$ level by the Duncan's multiple range test.

[c] Least significant difference at the 0.05 level.

tween these parameters existed. These findings suggested that for wheat, the main parameters associated with $N_2O$ emissions were soil temperature, SOC, and soil $NO_3^-$-N. Although soil moisture was strongly loaded in factor 3, the associations between soil moisture and other variables in factor 3 were not significant. Similarly for rice, two factors with eigenvalues ⟩ 1 were extracted, accounting for 90% of the total variance (Table IV). Factor 1 accounted for 76.84% of total variance and had very high loadings for soil $NO_3^-$-N, leaf area, $N_2O$ flux, and soil organic carbon. All these variables were positively associated. Factor 1 indicates that increases in $N_2O$ emissions were strongly associated with increases in soil $NO_3^-$-N, leaf area, and soil organic carbon for rice. Root and shoot dry weights were also positively related to $N_2O$ emissions but had factor loadings < 0.70 and hence were considered to be less important. Factor 2 accounted for 14% of total variance. Although factor 2 was highly loaded with shoot dry weight, root dry weight, and field water level, the association between these variables with $N_2O$ emission was not significant.

## CONCLUSIONS

$N_2O$ emissions showed significant differences for the rice and wheat varieties of the experiment conducted in the rice and wheat cropping systems at the North Bank Plain Agro-climatic Zone of Assam, India. The $N_2O$ emissions for the wheat varieties were primarily dependent upon soil parameters including soil temperature, SOC, and soil $NO_3^-$-N). The main parameters influencing $N_2O$ emission in the rice ecosystem were soil $NO_3^-$-N, leaf area, and SOC. These suggested suitable rice and wheat varieties emitting less $N_2O$ in an agroecosystem could be selected to develop biological mitigation strategy.

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TABLE IV

Principal factor loading matrix after varimax rotation for plant physiological parameters, soil properties, and $N_2O$ emissions of the rice and wheat seasons

| Season | Variable | Factor loading | | | Variance explained by the underlying factors |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | |
| | | | | | % |
| Wheat | $N_2O$ flux | 0.229 | 0.919[a)] | | 90.4 |
| | Soil $NO_3^-$-N | 0.569 | 0.717[a)] | −0.198 | 87.7 |
| | Soil organic C | 0.441 | 0.759[a)] | −0.410 | 93.9 |
| | Soil moisture | 0.102 | | 0.957[a)] | 92.8 |
| | Soil temperature | 0.165 | 0.856[a)] | 0.281 | 83.9 |
| | Leaf area | 0.899[a)] | 0.239 | −0.320 | 96.7 |
| | Shoot dry weight | 0.853[a)] | 0.327 | 0.394 | 99.0 |
| | Root dry weight | 0.892[a)] | 0.294 | 0.331 | 99.2 |
| | Eigenvalue | 4.798 | 1.588 | 1.051 | |
| | Variance explained (%) | 59.973 | 19.847 | 13.138 | |
| | Cumulative variance explained (%) | 59.973 | 79.820 | 92.958 | |
| Rice | $N_2O$ flux | 0.834[a)] | 0.213 | | 74.1 |
| | Soil $NO_3^-$-N | 0.943[a)] | 0.187 | | 92.4 |
| | Soil organic carbon | 0.830[a)] | 0.519 | | 95.9 |
| | Field water | | −0.972[a)] | | 94.8 |
| | Soil temperature | 0.591 | 0.691 | | 82.7 |
| | Leaf area | 0.915[a)] | 0.335 | | 95.0 |
| | Shoot dry weight | 0.509 | 0.831[a)] | | 95.0 |
| | Root dry weight | 0.653 | 0.737[a)] | | 97.0 |
| | Eigenvalue | 6.148 | 1.120 | | |
| | Variance explained (%) | 76.846 | 13.994 | | |
| | Cumulative variance explained (%) | 76.846 | 90.841 | | |

[a)]Factor loadings greater than 0.70 which are considered important.

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