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ESTIMATION OF METHANE EMISSION FROM RICE PLANTS GROWN IN ALLUVIAL SOILS OF ASSAM AND ITS BIOLOGICAL MITIGATION IN RELATION TO CROP GROWTH

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

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ABSTRACT

Rice fields serve as an important anthropogenic source of atmospheric methane (CH_4), a greenhouse gas implicated in global warming. The present thesis deals with the results of experiments on estimation of methane emission from rice fields in relation to plant growth and soil parameters. Experiments were conducted in the alluvial soils of North Bank Plain Agro-climatic Zone of Assam, India, in order to elucidate the relationship of methane emission with physiological characteristics of rice plants and soil physico-chemical characteristics. Methane emission was estimated from a) rainfed (unirrigated) monsoon rice (*Sali*), b) irrigated (*Boro*) and c) rainfed (unirrigated) upland (*Ahu*) rice ecosystems. The content of the thesis have been distributed over six chapters. Findings of individual chapters are discussed below.

Chapter 1 presents a brief introduction pertaining to the present investigation. The importance of greenhouse gases in general, and methane emission from rice fields in particular are highlighted. Justifications for the precise evaluation of methane emission from rice cultivars grown under different agroecosystems of Assam are provided. Objectives of the investigations are also presented in this chapter.

Chapter 2 presents a brief review of literature related to the present work. Various published reports describing the importance of methane emission from paddy fields and its relation with global warming are focused in this chapter. Literature available on the mechanisms of methane production, oxidation and emission along with the factors affecting methane emission from paddy fields are reviewed.

Chapter 3 describes the details of the materials and methods of estimation of methane emission from paddy fields. Methods employed for evaluation of physiological and anatomical characteristics of rice plants are presented. Details of the methods used for soil physico-chemical study and statistical analysis are provided in this chapter.

In **Chapter 4,** findings of the experiments are presented in the form of figures, tables and photographs.

Chapter 5 presents the discussions of the results of the present investigation. The outline of this chapter is briefly described below.

Experiments over two consecutive years during the monsoon season (August-November) of 2005 and 2006 elucidated the effects of physiological characteristics of rice plants on methane emission from paddy fields. Methane emissions from two high yielding varieties of rice *viz.* Bahadur and Piolee were recorded at different growth stages. Higher methane flux was recorded in variety Bahadur compared to Piolee. Higher photosynthetic rate of variety Bahadur was a contributing factor to profuse vegetative growth of this variety which resulted in higher flux rate of methane. Statistical analysis of growth parameters *viz.* leaf number and area, root volume and length and tiller number showed a positive correlation with methane emission. Higher grain yield and superior yield attributing parameters were recorded in variety Piolee.

Measurement of methane flux from irrigated agroecosystem for two consecutive years (February-June of 2006-2007) from Agni (traditional cultivar of rice) and Ranjit (high yielding variety) exhibited differences in emission behaviour. A higher seasonal integrated methane flux (E_{sif}) was recorded in Agni compared to Ranjit. Higher methane emission from the cultivar Agni was due to its luxuriant vegetative growth. Variety Ranjit recorded higher yield attributing parameters like higher thousand grain weight, filled grain (%), panicle dry weight and yield; coupled with lower rate of methane emission.

Methane emission was estimated from two improved rice varieties *viz.* Disang and Luit during rainfed (unirrigated) upland (*Ahu*) rice growing season (April-July, 2006). Higher seasonal integrated methane flux was recorded in cultivar Disang (E_{sif} = 1.38g m^{-2}) compared to Luit (Esif = 0.96g m^{-2}). Methane emissions from the cultivars were influenced by crop phenology and growth. Higher vegetative growth of cultivar Disang attributed to higher emission rate.

Plant-mediated transport is the primary route of methane emission from the paddy field to the atmosphere. Ten (10) rice cultivars were planted during monsoon season (August-November, 2006) to elucidate the influence of anatomical and physiological characteristics of rice cultivars on methane emission. Wide variation in CH_4 flux was noticed among the rice genotypes. Seasonal integrated CH_4 flux (E_{sif}) ranged from 8.74g m^{-2} to 12.46g m^{-2} among the cultivars. The tested rice genotypes could be ranked into three groups *viz.* low, medium and high methane emitting cultivars, based on their CH_4 flux potential.

A close association of methane emission with soil organic carbon content of the field was recorded. A highly significant positive correlation was found between methane emission and soil organic carbon content irrespective of agroecosystems. Soil organic carbon reached a maximum value at late tillering and panicle initiation stage of the crop, which coincided with the seasonal maxima of methane emissions. This trend was observed in all the agroecosystems independent of the cultivars.

Photosynthetic characterization of rice cultivars revealed that high-methane-emitting cultivars exhibited higher rate of photosynthesis during active vegetative growth period. On the other hand, higher leaf photosynthetic rate after panicle initiation coupled with an efficient translocation of photosynthates towards the developing grain contribute to higher grain yield in low-emitting-cultivars. It is hypothesized that in high-CH_4-emitting cultivars, a major portion of photosynthetic carbon products were translocated to the root and eventually released into the rhizosphere and utilized as substrate by methanogens leading to more

production of CH_4. Additionally, the extensive vegetative growth of these cultivars may enhance methane transport from the soil to the atmosphere.

Wide variation in CH_4 flux among the rice cultivars are also regulated by the anatomical and physiological characteristics of the plants. Microscopic analysis of stem portion showed that high and medium-CH_4-emitting cultivars recorded higher size of the medullary cavity, increasing the cross-sectional area of the stem for methane diffusion pathway. Scanning electron microscopic (SEM) analysis revealed higher stomatal frequencies in high-methane-emitting cultivars. Transpirational rates were also found to be higher in high-CH_4-emitting rice genotypes. It is hypothesized that a fraction of methane is released into the environment because of transpiration-induced bulk flow. These findings suggest that variation in the anatomical characteristics of shoot and leaf of the rice genotypes influence CH_4 emission from paddy fields.

In **Chapter 6**, salient findings from the different experiments are summarized and conclusions drawn are presented. Among the three rice agroecosystems, higher seasonal integrated methane flux (E_{sif}) was recorded in the monsoon (*Sali*) rice ecosystem followed by irrigated (*Boro*) and rainfed (unirrigated) upland (*Ahu*) rice ecosystems. In all the agroecosystems, cultivars with low methane emission exhibited higher yield potential due to increased photosynthate partitioning to panicles at the expense of the vegetative parts. The findings of the present investigation indicate that the use of high-yielding cultivars with higher photosynthate carbon translocation towards the grain would result in lower CH_4 emission. This is considered a suitable biological mitigation option for reducing methane emission to the atmosphere. Varietal characteristics of rice plant with lower emission of methane are important characteristics identified in the present investigation could be incorporated in the future plant breeding programme for development of rice varieties with low emission and higher productivity.

DECLARATION

I do hereby declare that the thesis entitled **"Estimation of Methane Emission from Rice Plants Grown in Alluvial Soils of Assam and its Biological Mitigation in Relation to Crop Growth"**, 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.

Kaushik Das

Place : Tezpur University, Tezpur

Date : 02.09.2008

(KAUSHIK DAS)

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CERTIFICATE

This is to certify that the thesis entitled **"ESTIMATION OF METHANE EMISSION FROM RICE PLANTS GROWN IN ALLUVIAL SOILS OF ASSAM AND ITS BIOLOGICAL MITIGATION IN RELATION TO CROP GROWTH"** submitted to the Tezpur University in the **Department of Environmental Science** under the School of **Energy, Environment and Natural Resources** in partial fulfillment for the award of the Degree of **Doctor of Philosophy** in **Environmental Science**, is a record of research work carried out by **Mr. Kaushik Das** under my supervision and guidance.

All helps received by him from various sources have been duly acknowledged.

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

(Dr. K. K. Baruah)
Professor and Head,
Department of Environmental Science,
School of Energy, Environment and Natural Resources,
Tezpur University.

Place: Tezpur University, Tezpur
Date: 2.9.2008

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The committee recommends for the award of the degree of Doctor of Philosophy.

Principal Supervisor **External Examiner**

Date: **Date:**

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Kaushik Das

Place : Tezpur University, Tezpur

Date : 02.09.2008 ***(Kaushik Das)***

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LIST OF ABBREVIATIONS

DAT	Days after transplanting
%	Percentage
μ M	Micro meter
μ mol	Micro mole
^{0}C	Degree celcious
g	Gram
ha	Hectare
hr	Hour
LAI	Leaf area index
m	Meter
M ha	Million hectare
m mol	Millimole
mg	Milligram
min	Minute
ml	Milliliter
MMO	Methane monooxygenase
MTC	Methane transport capacity
mV	Millivolt
NBPAZ	North Bank Plain Agro-Climatic Zone
PI	Panicle initiation
q	Quintal
Tg	Tera gram

Chapter 1

Introduction

1. INTRODUCTION

Current evidence for global warming and the prediction of significant climate change in the future has prompted worldwide interest on greenhouse gases. Global surface temperature has increased by about 0.2°C per decade in the past 30 years, which is similar to the predicted warming rate proposed in the 1980s in initial global climate model simulations with transient greenhouse gas changes (Hansen *et al.*, 2006). Greenhouse gases are those gaseous constituents of the atmosphere, which absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the earth's surface. These gases are nearly transparent to the incoming visible and shorter wavelengths of sunlight, but they absorb and re-emit a large fraction of the outgoing longer infrared radiation emitted by the earth. As a result of this, the greenhouse gases radiate large amounts of long wave-length energy downward to the earth's surface and thus radiant energy received on earth is increased (Crutzen, 1995). This phenomenon leads to the greenhouse effect, the primary cause of global warming. Carbon dioxide (CO_2), water vapour (H_2O), methane (CH_4) and nitrous oxide (N_2O) are the primary greenhouse gases in the earth's atmosphere. Moreover, there are number of other anthropogenic greenhouse gases in the atmosphere, such as CFC-11 and CFC-12, perfluorocarbons (PFCs, such as CF_4 and C_2F_6) and hydrofluorocarbons (HFCs, such as CH_2FCF_3 or HFC-134a). Although natural changes of greenhouse gases take place over time, but in recent years major increase in the greenhouse gases have been observed, which can be linked to increasing population and industrialization (Khalil, 1999). Various anthropogenic activities enhance the emission of greenhouse gases that accumulate in the atmosphere and increase radiative forcing resulting in warming of the earth's surface. For example, increase in CO_2 concentrations in the atmosphere during the 20th century and its radiative forcing was faster than the change during the past 22,000 years (Joos and Spahni, 2008). As the concentrations of the greenhouse gases increase, it is expected that the surface temperature of the earth will also increase. This

global warming is likely to trigger significant environmental changes, which is a major environmental issue of present time. The current concentration of a greenhouse gas in the atmosphere is the net result of the history of its past emissions and removals from the atmosphere. Long-lived greenhouse gases are chemically stable and persist in the atmosphere over time scales of a decade to centuries, so that their emission has a long-term influence on climate. The average rate of increase in the radiative forcing from the greenhouse gases is larger during the Industrial Era than during any comparable period of at least the past 16,000 years (Joos and Spahni, 2008).

Methane is an important greenhouse gas that traps thermal radiation from the earth's surface and plays an important role in the atmospheric chemistry (Lelieveld *et al.*, 1993; Khalil, 1999). A rapid increase in the concentration of atmospheric methane is one of the major concerns for global environment. Increases in CH_4 abundance in the atmosphere occur when emissions exceed removals. Atmospheric abundance of methane has increased by a factor of 2.5 since pre-industrial era (Jia *et al.*, 2002), which indicates that its concentration has been doubled in last 200 years (Singh *et al.*, 2003). Reports of Intergovernmental Panel on Climate Change (2007) clearly showed that atmospheric CH_4 concentrations varied slowly between 580 and 730 ppb over the last 10,000 years, but increased by about 1000 ppb in the last two centuries, representing the fastest changes in this gas over at least the last 80,000 years. The global atmospheric concentration of CH_4 has increased from a pre-industrial value of about 715 ppb to 1732 ppb in the early 1990s, and is 1774 ppb in 2005. In the late 1970s and early 1980s, CH_4 growth rates displayed maxima above 1% yr^{-1} (IPCC, 2007). Although, annual increase in atmospheric CH_4 has slowed recently, which has been attributed to decreasing anthropogenic emission from fossil fuels, but it is thought to be only a temporary pause (Bousquet *et al.*, 2006).

Although atmospheric abundance of methane is less than CO_2, it is approximately 21 times more effective in absorbing infrared radiation than CO_2 (Shine *et al.*, 1995).There are 200 CO_2 molecules for every CH_4 molecule in the atmosphere, but the greenhouse effect of CO_2 is only 3.5 times that of CH_4 (Evans, 2007). Increases in atmospheric CH_4

concentrations since pre-industrial times have contributed a radiative forcing of +0.48 ± 0.05 W m^{-2}, which remains second only to that of CO_2 in magnitude among all other greenhouse gases (IPCC, 2007). Multiple lines of evidence confirm that the post-industrial rise in methane concentration does not originate from natural sources but from anthropogenic activities (Cheng *et al.*, 2006). The total annual global emission of methane is estimated to be 420-620Tg / year (Khalil and Rasmussen, 1990), 70-80% of which is of biogenic origin (Bouwman, 1990).

This elevated methane concentration influences the photochemistry of the atmosphere and accounts for about 15% of the current increase in global warming (Batjes and Bridges, 1992). Most of the CH_4 in atmosphere is originated in anoxic environment (Hori *et al.*, 2007), but it is reported recently that CH_4 can also be emitted from plants under aerobic condition (Keppler *et al.*, 2006; Keppler and Rockmann, 2007). The accumulation of atmospheric CH_4 is attributed to various activities, mainly microbes mediated methanogenesis (biogenic CH_4) occurring in anoxic ecosystems and thermo-catalytic reactions (thermogenic CH_4). Thus, the sources of CH_4 are both abiotic and biotic in origin. The biogenic sources are the major contributors of atmospheric methane (Kumaraswamy *et al.*, 2000). Both abiotic and biotic sources of CH_4 comprise anthropogenic and natural emissions. The contributions of anthropogenic and natural sources to the global CH_4 budget are about 70% and 30%, respectively (Hogan *et al.* 1991). The anthropogenic sources of atmospheric methane include rice paddies, domestic ruminants, biomass burning, landfills, coal mining, oil and natural gas flaring, application of animal wastes and domestic sewage (Crutzen, 1991; Wilbanks and Kates, 1999). About 50% of the total annual CH_4 emission to the atmosphere is directly related to food production required to feed the exploding world population (Ishermann, 1994).

Flooded rice soils provide an optimum environment for methane production and emission (Conrad *et al.*, 2008) and are considered to be a major anthropogenic source for biogenic methane (Minami and Neue, 1994; Wassmann and Dobermann, 2008). Methane emission from flooded rice fields contributes up to 12% of global methane emission to the

atmosphere; methane emission from wet land rice agriculture is reported to account for 26% of the global anthropogenic methane budget (Neue and Roger, 2000). Therefore, the increase in flooded rice area is considered to be one of the factors responsible for continued increase in the atmospheric methane concentration (Cai and Mosier, 2000). Worldwide emission from rice fields has been estimated from reports from China, India, Vietnam, Korea, and the Philippines to be from 21 to 30 teragrams (1 teragram = 10^{12} g) per year (Sass *et al.* 2002).

Rice fields are subjected to a great deal of management practices including tillage, fertilization, irrigation, weeding and manure amendments. Such management practices can affect CH_4 emissions and play an important role in the atmospheric balance of the trace gases (Babu *et al.*, 2006). Rice is physiologically adapted to grow in wetland condition which is also ideal for CH_4 production. Submergence of rice fields stops the direct influx of atmospheric oxygen (O_2) into the soil. Such anoxic and chemically reduced soil environment favours the activities of anaerobic methanogenic bacteria (Verburg *et. al.*, 2006), which utilize organic substrates to generate CH_4 and CO_2 (Dubey, 2005). There are three pathways available for escape of methane from the reduced soil to the atmosphere. These pathways are: 1) molecular diffusion, 2) ebullition of methane and 3) methane transport through the rice plant; of these pathways, more than 90% is released through the rice plants (Neue *et al.*, 1994). Moreover, rice plants affect methane production in three distinct ways; first, they stimulate methanogenesis through the production of root exudates and sloughed-off tissues (Jimenez and Lal, 2006). Second, rice plants act as an active CH_4 oxidizing site in rhizosphere by supporting O_2 counter-transport through aerenchyma system (Denier Van Der Gon and Neue, 1996). Third, rice plants act as conduits for gas exchange since a major portion of CH_4 released into the atmosphere from paddy soil are transported by the tissue system of the plant (Banker *et al.*, 1995). Methane emission from paddy fields is the result of its production and oxidation in the soil and its subsequent transport to the atmosphere through rice plants (Kruger *et al.*, 2001).

Rice is one of the world's major staple foods and rice fields occupy approximately 15% of the world's arable lands (Maclean *et al.*, 2002). Since the majority of rice produced

in the world is in flooded paddies, methane emission from rice paddies is expected to increase with the increase in rice cultivation. Total area under rainfed low-land agroecosystem covers about 27% of global rice area which is a major source of anthropogenic methane (Parashar *et al.*, 1994). Contribution of upland rice, generally grown without much standing water, to total CH_4 budget is not significant. On the other hand, deepwater rice cultivated under intense inundated condition, contributes about 10% of the global methane from the rice sources (Wassmann *et al.*, 2000).

India produces 80 Mt of rice on an area of 42.30 M ha, corresponding to 28% of the global rice land (Sharma *et al.* 1995). The rice growing areas of India can be broadly categorized into rainfed and irrigated agroecosystems, representing about 52% and 48% of the total rice area of the country, respectively (Babu *et al.*, 2006). The harvest area of rice has increased by about 70% during last 50 years, and it is assumed that CH_4 emission has also increased proportionally (Yagi *et al.*, 1997). Therefore, the reduction in CH_4 emission from paddy fields is very important to stabilize its atmospheric concentration. World's annual rice production must be increased from a 1990 value of 473 million tones to 600 million tones by 2010 (Anastasi *et al.*, 1992) to meet the demand of increasing population. Scope of conversion of uncultivated land areas to cultivable paddy fields is not possible because of limited land resources. Therefore, desired higher rice grain production must be achieved primarily by intensifying the rice cropping system. It indicates that rice cultivation with irrigation will be one of the major cultivation practices in future rice production technologies. Moreover, intensification of rice cultivation will also include multiple cropping and such transformation from traditional agriculture to an intensified one will entirely alter the previous crop management practices. Such transformations may lead to more greenhouse gas emission from rice fields.

Assam, the largest state of northeast India, is predominantly a rice growing state. Rice is grown throughout the year in different agroecosystems *viz.* irrigated ecosystem (locally known as *Boro* rice), rainfed lowland and medium land ecosystem (*Sali* rice), rainfed upland ecosystem (*Ahu* rice) and deep-water ecosystem (*Bao* rice). Farmers of this

region cultivate high yielding rice varieties along with traditional cultivars. It is therefore, important to evaluate precise emission characteristics of methane from rice cultivars grown under different agroecosystems of Assam. Methane emissions from different rice agroecosystems need to be reduced in order to stabilize the global climate. Therefore there is an urgent need to establish agro-technologies that will increase rice production and simultaneously reduce CH_4 emission from paddy fields. Selection of high yielding rice cultivars with low amount of CH_4 emission may be an effective biological mitigation option (Gogoi *et al.*, 2008). Thus the relationship between rice production physiology and emission of CH_4 from rice plants emerges as a major scientific and policy issue. In the present study, attempt was made to establish the relationship of CH_4 emission from traditional and improved rice cultivars with growth, grain filling and yield characteristics grown at different ecosystems with the following objectives:

Objective 1. Precise emission estimation of methane from different rice agroecosystems of alluvial soils of Assam.

Objective 2. To investigate the relationship of plant growth parameters and soil parameters with methane emission from rice plants.

Objective 3. Analysis of intervarietal difference in methane flux from rice plants as biological mitigation option in relation to growth and yield.

Chapter 2

Review of Literature

2. REVIEW OF LITERATURE

The temperature of the surface of the earth is regulated by a few atmospheric trace gases. These gases trap and re-emit the heat released from the surface of the Earth as infra-red radiation and have been termed as the greenhouse gases. It is well documented that the concentrations of trace gases in the atmosphere change naturally over time. However, in recent years significant increase in the greenhouse gases in the atmosphere have been reported, which is primarily associated with anthropogenic activities (IPCC, 2007). Because of increased concentrations of the greenhouse gases in the atmosphere, the surface temperature of the earth has been elevated (Hansen *et al.*, 2006). Joos and Spahni (2008) reported that global climate change, which is primarily anthropogenic in origin, is progressing at a speed that is unprecedented at least during the last 22,000 years.

Methane is a potent greenhouse gas and originates both from anthropogenic and natural sources (Bousquet *et al.*, 2006). It has pronounced influence on the atmospheric chemistry leading to global climate change (IPCC, 2007). The sources of atmospheric CH_4 are both biotic and abiotic in origin. The abiotic sources of CH_4, such as mining, transport, fossil fuels and biomass burning, contribute about 20-30% to the global CH_4 budget, and about 70% is of biotic origin (Kumaraswamy *et al.*, 2000). Abiotic and biotic origins of CH_4 comprise both anthropogenic and natural sources. The contributions of anthropogenic and natural sources to the global CH_4 budget are about 70% and 30%, respectively (Hogan *et al.* 1991). The total annual source strength of methane from all anthropogenic origins is reported to be 550 Tg (Sass and Fisher, 1994). It is reported that each year methanogens produce about 400 million metric tons of CH_4 from biogenic sources (Ferry, 1997). Although, recently it is reported that CH_4 is emitted from plants under aerobic condition (Keppler *et. al.*, 2006; Keppler and Rockmann, 2007), which is being contradicted by Dueck *et al.* (2007). The biogenic methane is mostly produced by methanogenic *archaea* (methanogens) in anoxic and chemically reduced soil environments i.e. in flooded rice fields

(Hori *et al.*, 2007). Among the various sources of atmospheric methane, rice paddy is one of the most significant contributors (Minami and Neue, 1994). The process involved in the efflux of CH_4 from paddy fields to the atmosphere include three primary mechanisms: 1) methane production (methanogenesis) in the soil by methanogenic microorganisms, 2) methane oxidation (methanotrophy) by methanotrophs and 3) rice plant mediated methane transport from the soil to the above ground atmosphere (Conrad *et al.*, 2008; Jimenez and Lal, 2006; Denier Van Der Gon and Neue, 1996; Banker *et al.*, 1995). In this complex and dynamic process of methane production, oxidation and emission, rice plant has three major roles: 1) rice plant provides substrates for methanogenic microbes for CH_4 production in anoxic soil, 2) acts as a conduit for CH_4 transport from reduced soil to the atmosphere through well developed inter cellular air spaces, and 3) establishes methane oxidizing environment by diffusing oxygen in the rhizosphere. Therefore, CH_4 production, oxidation and its subsequent emission is regulated by a set of close and complex interactions among rice plants, microbes and environment (Verburg *et al.*, 2006). In this chapter, the literature on production, oxidation and emission of methane from flooded rice fields are reviewed. Various environmental and plant factors that affect CH_4 production, oxidation and emission are also reviewed.

2.1. Methane production, oxidation and emission from rice fields

2.1.1. Methane production

Despite the fact that rice paddy fields are contributing a significant portion to global methane budget, majority of the organisms responsible for methane production in paddy fields have remained almost uncultivated and thus uncharacterized (Sakai *et al.*, 2007). Methanogens are unicellular, strictly anaerobic organisms, which were previously considered bacteria but now are recognized as a separate phylogenetic domain called *archae* (Garcia, 1990). The type of methanogens colonizing rice roots has a potentially important

impact on the global CH_4 cycle (Conrad *et al.*, 2008). Methanogens can be categorized under three major groups. Group I includes *Methanobacterium* and *Methanobrevibacter*, Group II comprises *Methanococcus*, and Group III includes *Methanospirillum* and *Methanosarcina* (Garcia, 1990). They proliferate and grow in anoxic environments, such as sediments and the digestive tract of animals (Topp and Pattey, 1997). Methanogens play a crucial role in the degradation of complex organic compounds in such anaerobic and reduced conditions. Most methanogens are mesophilic, able to function in temperature ranging from 20 to 40^0C (Topp and Pattey, 1997). They primarily utilize acetate (contributes about 80% to CH_4 production) as a carbon substrate but other substrates like H_2/CO_2 and formate may also contribute 10-30% to CH_4 production (Chin and Conrad, 1995). All methanogens utilize NH_4^+ as the primary nitrogen source, although the ability of molecular nitrogen fixation and the presence of *nif* genes are reported in some methanogens (Palmer and Reeve, 1993).

The mechanism of methanogenesis in anoxic paddy fields has widely been investigated (Dubey, 2005). However, information regarding methanogenic population in paddy fields is limited. Rajagopal *et al.* (1988) were the first to report on isolation and characterization of methanogens from Louisiana paddy fields; they reported the presence of two *Methanobacterium*-like strains and two *Methanosarcina*-like strains in paddy soils. Joulian *et al.* (1998) determined the methanogenic populations from the paddy fields of France, the Philippines, and USA. Their results suggested the dominance of *Methanobacterium spp.* and *Methanosarcina spp.* among the culturable microorganisms. Apart from they are being present in rice root rhizosphere (Lehmann-Richter *et al.*, 1999), methanogens were reported to be abundant in root extracts of mature rice plants (Reichardt *et al.*, 1997). Fetzer *et al.* (1993) isolated four genera (*Methanobacterium, Methanosarcin, Methanobrevibacter* and *Methanoculleus*) from Italian rice fields. Kudo *et al.* (1997) reported the presence of *Methanosarcina, Methanogenium, Methanosaeta* and *Methanoculleus*-like organisms in rice paddy fields of Japan. Similarly, *Methanobacterium* and *Methanobrevibacter spp.* were isolated from subtropical Japanese rice fields (Adachi, 1999). A different group of methanogenic community has been reported which is closely

associated with rice root and is responsible for direct release of methane from the root system of rice (Le *et al.*, 1996). Recently, for the first time isolation of a methanogen (called strain SANAE) belonging to an abundant and ubiquitous group of methanogens called rice cluster I (RC-I) has been reported (Sakai *et al.*, 2007).

2.1.1.1. Methanogenesis

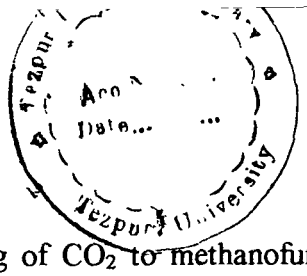
Methane is produced in the anoxic environment of paddy soil by bacterial decomposition of organic matter (Dubey, 2001). The organic substrates converted to CH_4 are derived primarily from plant derived organic materials, and from organic matter incorporated in soil in the form of organic manures (Dannenberg and Conrad, 1999). Methanogens mediated anaerobic degradation of organic matter involves four major steps: 1) hydrolysis of polymers by hydrolytic organisms, 2) acid formation from simple organic compound by fermentative bacteria, 3) acetate formation from metabolites of fermentations carried out by bacteria, and 4) methane formation from acetate, H_2/CO_2, simple methylated compounds or alcohols and CO_2 (Yao and Conrad, 2001). Methane is produced in anaerobic rice soils only after the sequential reduction of O_2, nitrate, manganese, iron and sulphate, which serve as electron acceptors for oxidation of organic matter to CO_2 (Yao *et al.*, 1999). Methanogenesis from all substrates requires a variety of unique coenzymes, some of which are exclusively found in methanogens (Ludmila *et al.*, 1998). At least nine methanogene-specific enzymes are involved in the pathway of methane formation from H_2 and CO_2 (Shima, 1998). In paddy soil, acetate and H_2 are the two main intermediate precursors for CH_4 formation (Yao and Conrad, 1999). Papen and Rennenber (1990) described two major pathways of CH_4 production in submerged anoxic soil environment:

(1) Methanogenesis from H_2/CO_2 :

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

(2) Methanogenesis from acetate :

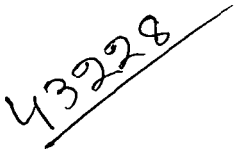
$$CH_3COOH \rightarrow CH_4 + CO_2$$



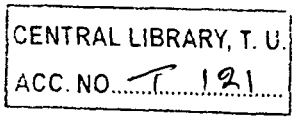
The first step of H_2/CO_2 pathway comprises the binding of CO_2 to methanofuran (MFR) and its H_2 dependent reduction to formyl-MF (first stable intermediate compound of the pathway). The formyl moiety of the formyl-MF is transferred to tetrahydromethanopterin (H_4MPT) and subsequently forms methenyl-H_4MPT, methylene-H_4MPT and methyl-H_4MPT (Dubey, 2005). The methyl group is then transferred to coenzyme M (2-mercaptoethane sulfonate) giving rise to methyl coenzyme M (methyl-CoM). Methane is produced by reduction of methyl-CoM catalysed by methyl-CoM-reductase. The various reaction steps involved in the process of methanogenesis from H_2/CO_2 in anoxic condition have been elaborately reviewed (Blaut, 1994; Jones, 1991; Shima, 1998).

Acetate is the most abundant intermediate of organic matter degradation in anoxic rice field soil and is converted to CH_4 and/or CO_2 (Hori *et al.*, 2007). Aceticlastic methanogenic archaea (i.e., *Methanosarcina* spp. and *Methanosaeta* spp.) utilize acetate during methanogenesis (Conrad *et al.*, 2006) which originates with its activation to acetyl-CoA. This process involves three different enzymes i.e. *acetate kinase*, *phosphotans acetylase* and *acetyl-CoA synthatase* (Dubey, 2005). Breakdown of acetyl- CoA releases a methyl group, which is then transferred to a corrinoid-Fe-S protein. In the subsequent steps, the methyl moiety is transferred to H_4MPT. Further pathway follows the reaction sequence from methyl H_4MPT to CH_4 similar to the utilization of the CO_2/H_2 (Blaut, 1994).

2.1.2. Methane oxidation



Several chemical and biological processes are involved in the process of consumption of atmospheric methane in the global methane cycle. However, the only well established biological sink for atmospheric methane is its oxidation in aerobic soils by methanotrophic bacteria. This microbial oxidation mechanism may contribute up to 10-20% to the total methane destruction (Reeburgh *et. al.*, 1993). Minami *et al.* (1993) estimated the total terrestrial CH_4 consumption to be between 7 and 78 Tg y^{-1}. Uptake of atmospheric CH_4 through biological oxidation has been reported in a variety of rice agroecosystems. First



evidence of plant associated CH_4 oxidation came from studies with microcosms (Frenzel, 2000). Although, rice field is an important source of CH_4, its oxidation in unflooded paddy soil after harvest could also be important for the global budget of methane. Gilbert and Frenzel (1998) found that a part of the CH_4 produced in paddy soil is oxidized either in the surface layer of the paddy soil or in the rhizosphere of rice plants.

2.1.2.1. Methanotrophs

Methanotrophs are gram negative, aerobic Proteobacteria (Conrad, 1999), which oxidize CH_4 with the help of methane monooxygenase (MMO) enzyme. Methanotrophic bacteria are present in the aerobic soil layer, rhizosphere (Gilbert and Frenzel, 1998) and on the roots and stem bases of rice plants (Watanabe *et al.*, 1997). They are well adopted to high or low temperature, pH and salinity (Trotsenko and Khmelenina, 2002). These bacteria are classified into three groups (Type-I, Type-II and Type -X) based on the pathways used for assimilation of formaldehyde and other physiological and morphological features (Hanson and Hanson, 1996). The Type-I group is represented by the *Methylomonas, Methylocaldum, Methylosphaera, Methylomicrobium* and *Methylobacter*. The Type-II comprises *Methylosystis* and *Methylosinus*. The members of the genus *Methylococcus* occupy an intermediate position and have been kept in to a separate group, Type-X (Hanson and Hanson, 1996).

All types of methanotrophs are reported to be present in rice fields (Frenzel, 2000). Henckel *et al.* (1999) found that activity of both Type-I and Type-II methanotrophs were stimulated in unsaturated soils of rice fields. Type II methanotrophs were found to dominate in unplanted, unfertilized soils, whereas the presence of rice plant was an essential factor for Type-I methanotrophs to proliferate (Bodelier *et al.*, 2000). Two strains of Type-II methanotrophs were isolated from Italian paddy soils (Gilbert and Frenzel, 1998). It is reported that the population size and activity of methanotrophs in paddy fields depends upon concentration of CH_4 (Bender and Conrad, 1992; Nayak *et al.*, 2007) and NH_4^+-N (Joulian *et*

al., 1997) in the soil. Population size of methanotrophs in soil planted with rice increases with time (Bosse and Frenzel, 1997). Recently Nayak *et al.* (2007) reported that methane oxidation rates significantly differed among the different growth stages of the rice crop Denier Van der Gon and Neue (1996) reported that CH_4 emission from rice plants one week before panicle initiation increased by 40% if CH_4 oxidation in the rhizosphere was blocked.

2.1.2.2. Methanotrophy

The oxidation of methane by methanotrophs is initiated by methane monooxygenase (MMO) enzyme. The MMO occurs in two forms: as a membrane bound particulate form (sMMO) in all types of methanotrophs, and as a soluble form in Type-II and Type X methanotrophs (Mancinelli, 1995). The activation of methane is achieved in the initial step by the MMO which converts CH_4, O_2 and reducing equivalents to methanol and H_2O (Conrad, 1999), i.e.:

$$CH_4 + O_2 + 2NAD(P) \rightarrow C H_3 OH + H_2O + 2 NAD(P)$$

The reducing equivalents are supplied by the subsequent dehydrogenation of methanol (Conrad, 1999). Two main CH_4 oxidation pathways, catabolic and anabolic are present in methanotrophs. Through the catabolic pathway methanotrophs oxidize methane to CO_2 via methanol, formaldehyde, and formate catalyzed by the enzymes: methane monooxygenase, methanoldehydrogenase, formaldehyde dehydrogenase and formate dehydrogenase, respectively. In this pathway energy is released but carbon is not incorporated into cellular biomass. The anabolic pathway may be further divided into two sub-pathways, ribulose monophosphate (RuMP) pathway and serine pathway. In both these pathways carbon of methane is incorporated in cellular biomass at the level of formaldehyde. Carboxylic acids and phosphoglycerated sugars are intermediary products in serine and ribulose monophosphate (RuMP) pathway, respectively. Type-I and Type-X methanotrophs follow RuMP pathway whereas serine pathway is followed by Type-II and Type-X methanotrophs (Hanson and Hanson, 1996).

2.1.3. Methane emission

Methane, the product of methanogenesis, escapes to the atmosphere from the chemically reduced paddy soil to the above ground atmosphere via three pathways: 1) molecular diffusion, 2) ebullition and 3) plant mediated transport. Cheng *et al.* (2006) reported that the CH_4 emitted by plant-mediated transport and ebullition-diffusion accounted for 86.7 and 13.3% of total emissions, respectively.

2.1.3.1. Molecular diffusion of methane

Molecular diffusion of CH_4 across the overlying water of the rice field to the atmosphere is a function of surface-water concentration of CH_4, wind speed and CH_4 supply to the surface water (Sebacher *et. al.*, 1983) Methane diffusion across the water present in paddy field is a very slow process (Rothfuss and Conrad, 1993) because the diffusion rate of gaseous CH_4 is very low in liquid phase (about 104 times slower than diffusion through the gas phase), therefore, it hardly contributes to the total CH_4 flux (Aulakh *et. al.*, 2001).

2.1.3.2. Ebullition of methane

Methane escape from the soil in the form of bubbles, called ebullition of methane, is a physical process. Ebullition of CH_4 from sediments is a common and significant mechanism accounting for 49-70% of the total flux in natural wetlands (Wassmann and Martius, 1997). However, on average, ebullition only contributes 10-20% to the seasonal methane emission from paddy fields (Nouchi *et al.*, 1994). But during the early stage of rice growing season, when methane production in the soil is high (due to organic fertilization), the seasonal contribution of ebullition may be increased (Denier Van Der Gon, and Neue, 1995; Wassmann *et al.*, 1996). Mattson and Likens (1990) reported influence of solar radiation, water temperature, air pressure and local water table on ebullition. Methane

emission to the above ground atmosphere through ebullition is hardly found in cloudy or rainy days (Nouchi *et al.*, 1994). When floodwater recedes and the soil falls dry, all entrapped methane in the soil is released via the air-filled pores (Wassmann *et al.*, 1994). Ebullition of methane is more after a prolonged period of submergence, as more methane has been entrapped in the soil (Watanabe and Kimura, 1995).

2.1.3.3. Plant mediated methane emission

Rice plants are mainly cultivated in flooded paddy fields and are dependent on oxygen transport from the above ground environment to the root through the plant to maintain aerobic root metabolism (Groot *et al.*, 2005). Due to oxygen consumption by rice-roots, aerobic microorganisms and soil fauna, the oxygen concentration in the soil is depleted and the plants develop additional aerenchyma in roots and shoots to provide a pathway for oxygen to the roots necessary for aerobic respiration (Jackson and Armstrong, 1999). This capability of the rice plant to transport gas is essential to survive submerged conditions (Colmer, 2003). According to Beckett *et al.* (1988) gas transport in rice plants is a diffusive process; it is usually measured for entire plants (Aulakh *et al.*, 2000b). Various investigations have provided important information on the importance of internal gas transport for plant functioning and showed how gas transport is influenced by temperature (Hosono and Nouchi, 1997), redox conditions (Kludze *et al.*, 1993) and rice cultivar (Aulakh *et al.*, 2000a). Gas transport through the rice plant occurs through a serial circuit of gas-flows from the above-ground atmosphere through shoot aerenchyma, a root-shoot transition, root aerenchyma and to some degree across a root barrier. The root barrier in rice is formed at flooded conditions (Colmer *et al.*, 1998) and may result from sclerenchymatous fibres with thick secondary walls (Clark and Harris, 1981) and represents a physical barrier to gas losses from the root (Colmer, 2003). Correlations between whole plant gas transport capacities and aerenchyma (Aulakh *et al.*, 2000b) and tiller number (Aulakh *et al.*, 2000a)

have been reported. The root-shoot transition zone represents the most important resistance to gas transport in rice plants (Butterbach-Bahl *et al.*, 1997; Hosono and Nouchi, 1997).

The ventilation system in rice plants also plays an important role in methane transport from the rhizosphere to the aerial atmosphere. It was found that the methane concentration in the medullary cavities of rice plants was about 2900 times higher than that of ambient air (Nouchi *et al.*, 1990). Plant mediated transport is the primary mechanism for the CH_4 emission from paddy fields, and contributes 60-90% to the total CH_4 flux (Wassmann *et al.*, 2000). According to a hypothetical model forwarded by (Nouchi *et al.*, 1990), methane from the soil-water enters the cell-wall of root epidermis, and then diffuses through the cell-wall of the root-cortex. Methane is then gasified in the root cortex and transported to the shoots via lysigenous intercellular spaces and aerenchyma. Eventually, CH_4 is released primarily through the micropores in the leaf sheath of the lower leaf position (Nouchi *et al.*, 1990). Subsequently, Nouchi and Mariko (1993) reported that in rice, a major portion of CH_4 is also released from the culm.

Relationship of plant mediated methane transport with leaf transpiration is not very clear as methane emission does not depend on opening or closing of stomata (Nouchi *et al.*, 1990) and no methane has been detected in the xylem sap (Wang *et al.*, 1997). Therefore it is suggested that methane emission from rice plant is independent of the transpiration rates (Seiler *et al.*, 1984). However, Allen *et al.* (2003) observed that highest CH_4 efflux coincides with increased transpirational rate and suggested that soil water flow to the roots deliver more dissolved CH_4 to the rice plant during periods of rapid transpiration. Similarly, Chanton *et al.*, (1997) observed a close relationship between diurnal variations in the CH_4 emission and transpirational rate and suggested that although CH_4 is transported by rice plants predominantly via molecular diffusion, a fraction was also released due to transpiration induced bulk flow. Their suggestions clearly indicate the role of leaf stomata in the process of plant mediated methane emission. Wang *et al.*, (1997a) observed that the leaves are the important methane releasing sites especially during the early growing stages of rice plant when the stem and internodes were relatively small. They reported that about 50%

of the CH_4 was released from the leaf blades of rice before shoot elongation but a lesser amount of CH_4 is emitted through leaves, as plant grew older blades (Neue *et al.*, 1997). During this period, the development of nodes provided the major release pathway of CH_4 to the atmosphere. Some cracks in junction point of internodes have been identified and Wang *et al.* (1997) described these cracks as major methane releasing sites. Therefore, for an efficient gas exchange between the root and the rhizosphere, cracks or openings present in the root system may play an important role. By using scanning electron microscopy, Butterbach-Bahl *et al.* (2000) confirmed the existence of cracks around the sites of new roots emerging from primary root. They pointed out that the presence of significantly fewer and smaller aerenchyma lacunae at nodal region of the culm base would restrict further upward transport of CH_4 through the primary tiller. Conversely, it would lead maximum diversion of CH_4 to secondary tillers and leaf sheaths (Butterbach-Bahl *et al.*, 2000). Leaf sheath and leaf blades have several fold greater density and amount of large sized aerenchyma lacunae and therefore CH_4 would find relatively low resistance in diffusion and release to the atmosphere. Although micropores present in the basal portion of leaf sheath were described as the main site of methane release by Nouchi *et al.* (1990), it was also pointed out by them that the micropores, surrounded by sclerenchyma, are not linked to the lysigenous intercellular space. Moreover, the presence of micropores in the leaf sheath of different rice cultivars was not confirmed by other workers (Butterbach-Bahl *et al.*, 2000). Therefore, the intercellulars, located between the epithel cells and closely related to the leaf sheath stomata may have a crucial role in plant mediated methane transport. Butterbach-Bahl *et al.* (2000) logically assumed a link of the stomata with the lacunae via these intercellulars, and suggested that stomata of the leaf sheath were the main site of methane release. Gogoi *et al.* (2005) reported a positive relationship of methane emission with leaf area of rice cultivars indicating the relationship of leaf stomata with methane flux.

2.2. Factors affecting methane oxidation, production and emission from paddy fields

2.2.1. Factors affecting methane oxidation

2.2.1.1. Concentration of methane and soil moisture

Methane oxidizing activity of methanotrophs is highly sensitive to the CH_4 concentration in the surrounding atmosphere (Bender and Conrad, 1993; Nayak *et al.*, 2007). An atmosphere with enhanced CH_4 concentration increases the population of methanotrophs and thereby enhances the process of methanotrophy (Mancinelli *et al.*, 1991). The threshold value of methane oxidation (below which no CH_4 consumption occurs) is much lower for soils than for sediments (Born *et al.*, 1990). The rate of methane oxidation is probably regulated by the supply of CH_4 to the oxidation-zone (King, 1992). Methane oxidation is reported to be sensitive to soil water deficit, soil moisture content below 20% of the water holding capacity significantly reduces the process of methanotrophy (Bender and Conrad, 1995; Jackel *et al.*, 2001). Cai and Mosier (2002) reported that the optimum moisture content of paddy soils for CH_4 oxidation depends on the methanotrophic bacteria in relation to the prevailing water regime; they also showed that desiccation damages the CH_4-oxidation ability of permanently flooded paddy soil more severely than that of frequently well drained soils.

2.2.1.2. Temperature

In general, the activity of microbial community is very much sensitive to changes in temperature. However, several reports describing the effect of temperature changes on the activity of methanotrophs are contradictory. For example, Whalen *et al.* (1990) showed that in methane enriched atmosphere, CH_4 oxidation rate is increased with increasing temperature within the limit of 5-20°C. On the other hand, Bender and Conrad (1995) observed a linear

response of methane oxidation in the temperature range of 20-35°C; however they also showed that 13-38% of the maximum methane oxidizing activity persists even at 0°C.

2.2.1.3. Soil nutrient and soil pH

Inorganic nitrogen affects the process of CH_4 oxidation by shifting the population structure of methanotrophs in soil; moreover, the kinetics of methanotrophy is also altered by inorganic nitrogen (Dubey *et al.*, 2002). This may affect the threshold value for CH_4 oxidation (King, 1992). Nitrate-nitrogenous fertilizers generally do not affect the CH_4 consumption but ammonium nitrogen may completely stop CH_4 oxidation (Hutsch *et al.*, 1994). Ammonium inhibition of methane oxidation is explained by the process of competitive inhibition at the enzyme level. This competitive inhibition occurs because of the similar molecular size and structure of ammonium and methane (Schimel, 2000). As a result, the enzyme methane monooxygenase (MMO) can bind to ammonium ion. Nayak *et al.* (2007) reported stimulation of methane oxidation following the application of mineral fertilizers or compost, which indicates nutrient limitation as one of the factors affecting the oxidation process. Combined application of compost and mineral fertilizer, however, inhibited CH_4 oxidation probably due to N immobilization by the added compost (Nayak *et al.*, 2007). It has been shown that CH_4 oxidation at pH 6.3 is greater than at pH 5.6; this process is completely inhibited at pH 4.8-5.1 (Hutsch *et al.*, 1994). However, in some cases, oxidation has been reported at pH as low as 3.2 (Sinha, 1995). In general, low pH has an inhibitory effect on methane oxidation, although the exact mechanism involved for this effect is not fully understood (Hutsch *et al.*, 1994).

2.2.1.4. Availability of oxygen

Methanotrophy is an oxidative phenomenon and therefore methane oxidation is entirely an oxygen dependent process. Oxygen availability in paddy fields depends upon the porosity of soil. As the porosity of soil increases, a decreased volume of water is distributed in pore volume, decreasing the thickness of the water film. This elevates the rate of substrate (CH_4) supply to the methanotrophs for oxidation of methane (Mancinelli, 1995). Low level of oxygen in the of wetland rice soil results in strong competition for O_2 among the methanotrophs (King, 1992) and reduces methane oxidation.

2.2.2. Factors affecting methane production and emission

Methane is produced in the anoxic environment of paddy soil by bacterial decomposition of organic matter. The organic substrate is derived primarily from organic materials from plant and soil-incorporated organic manure (Dannenberg and Conrad, 1999). The process of methanogenesis is controlled by various factors e.g. pH, Eh and texture of soil, temperature, growth and phenology of rice, diurnal and seasonal effect, rice cultivars, organic manures, fertilizer application etc.

2.2.2.1. Soil pH, Eh and texture

Methanogenesis in anoxic rice soils is pH-sensitive. Submergence of rice-soil causes the soil pH to stabilize between 6.5 and 7.2 (Ponnamperuma, 1972). The optimum range for methane production ranges between 6.7 and 7.1(Bouwman, 1990; Wang *et al.*, 1997b), and therefore submergence of rice field provides an optimum soil environment for methanogenesis. However, the optimum pH for methane production varies with the type of soil. The optimum pH range for methanogenesis was reported to be 7.5-8.5 in four different Indian rice soils (Parashar *et al.*, 1991).

Submergence of paddy field leads to soil anaerobiosis, measured in terms of soil redox potential (Eh). Anoxic soil condition results in a sharp decline in Eh values. Yagi and Minami (1990) reported that necessary redox potential for the initiation of CH_4 production in paddy soils varied from -100 to -200 mV. Masscheleyn *et al.* (1993) found the threshold Eh for methane production to be -150 mV. Under such conditions, rice soils containing higher amounts of easily degradable organic substrates (acetate, formate, methanol, methylated amines, etc.) and low amounts of electron acceptors (Fe^{3+}, Mn^{4+}, NO_3^-, SO_4^{2-}) are likely to show high production of CH_4. In the sequential oxidation-reduction, molecular O_2 is the first to be reduced at an Eh of about +30 mV followed by NO^{3-} and Mn^{4+} at 250 mV; Fe^{3+} at +125 mV ; and SO_4^{2-} at -150 mV (Patrick, 1981).

As texture determines various physico-chemical properties of soil, it can also influence CH_4 production. Jackel *et al.* (2001) found that rates of CH_4 production increased with increase in the aggregate size of the soil. A negative correlation between CH_4 emission and clay content of soil was reported (Sass and Fisher, 1994; Denier Van der Gon and Neue, 1996). Clay materials can protect soil organic matter from degradation and higher clay content may promote soil entrapment of CH_4 (Wang *et al.*, 1993a). Consequently a net CH_4 emission from clay rich soil is reduced. On the other hand, calcareous soils showed rapid formation of methane upon flooding. The mechanism is that in calcareous soil, high level of $CaCO_3$ buffers the pH to the optimum range for methanogenesis (Neue and Roger, 1993). In coarse textured soil, having a high percolation rates, redox potential often has positive values. In such rice-soils, CH_4 production is considerably suppressed due to high Eh values It is reported that in north India from coarse textured sandy loam paddy soils with a high percolation rate, very low CH_4 emission was recorded even when the fields were flooded (Jain *et al.*, 2000).

2.2.2.2. Soil Temperature

The influence of temperature on CH_4 production is well documented (Thurlow *et al*, 1995). The process of decomposition of organic materials, from which the methanogenic substrates are generated, is strongly influenced by temperature (Chin and Conrad, 1995). An increase in temperature accelerates the decomposition of organic matter (Tsutsuki and Ponnamperuma, 1987), which eventually increases the process of methane production and subsequent emission. In general, 10-30% increase in CH_4 flux can be observed with every 1^0C increase in soil temperature (Parashar *et al.*, 1996). Wassmann *et al.* (1998) observed a rapid rate of CH_4 production with temperatures between 25 and 35°C. Most of the methanogens exhibit optimum growth at a temperature range of 30^0C to 40^0C (Vogels *et al.*, 1988). Hattori *et al.* (2001) recorded optimum temperature of 40°C for CH_4 production in Japanese paddy fields due to dominance of methanogenic population at this temperature. Methane production at soil temperature of 30^0C was much higher (by a factor of 2.5 to 3.5) than that in 17^0C at flooded soil samples (Conrad *et al.*, 1987). Diurnal variations in CH_4 emission from rice fields was also found to be correlated with soil temperature (Neue *et al.*, 1995).

2.2.2.3. Growth period and crop phenology

Growth period and phenology of rice influence production and emission of methane from paddy fields. Lower CH_4 fluxes was recorded in the early growth period of rice plant, which increased gradually during mid to late season and dropped to very low level before or after harvest (Sinha, 1995; Wassmann *et al.*, 2000a; Gogoi *et al*, 2005). More than 50% of CH_4 was emitted in the first half of the growth period in Thailand rice fields (Jermsawatdipong *et al.*, 1994), while CH_4 emissions in Japanese rice fields occurred mainly in the second-half of the growth period (Kimura *et al.* 1991). Jermsawatdipong *et al.* (1994)

suggested that the relatively high temperatures at the beginning of rice growth in the tropical climate results in rapid decomposition of organic materials which is the reason for higher CH_4 production from the beginning of rice growth. Seiler *et al.* (1984) recorded higher CH_4 emission rate at the end of heading and flowering stage of rice plants in Spain. During the reproductive stage of rice plant emits 90% of the total methane flux of the whole crop season (Holzapfel-Pschorn *et al.*, 1986).

2.2.2.4. Diurnal and seasonal variations

Emission rates of CH_4 generally increase rapidly after sunrise, reach a peak in the early afternoon then decline rapidly and level off at night. Methane emission rates during the early and late phase of plant growth exhibited a distinct maximum in the early afternoon, while this pattern is less pronounced in the middle stage of plant growth (Aulakh *et al.*, 2001). Three seasonal maxima of methane flux are reported from Italy, the first shortly after flooding, the second during the vegetative growth stage and third during the grain filling and maturity stage of rice plants (Schutz *et al.*, 1989). Two distinct methane emission peaks, one at active vegetative growth and the other at panicle initiation stage of the crop were reported by different workers (Neue *et al.*, 1995; Gogoi *et al.*, 2005). Such methane flux maxima have been attributed to the higher availability of substrates in the rice rhizosphere (Adhya *et al*, 1994). Some workers reported an initial methane emission maximum that occurs shortly after transplanting, caused by the fermentation of easily degradable soil organic matter in the soil (Sass and Fisher, 1992). Methane emission from rice fields in Phillipines was higher in dry season than in wet season (Denier Van der Gon *et al.*, 1992), which was attributed to higher temperature during the dry season. However, it is also reported that seasonal variation in CH_4 production and emission depend on plant development with no seasonal temperature dependence (Sass *et al.*, 1991). Seasonal variation in CH_4 emission was also reported by Butterbach-Bahl *et al.* (1997) and it was found that rate of CH_4 emission depended on the fertilizer application. Water regimes, cultural practices and temperature changes modify the

general seasonal pattern of CH_4 emission (Neue *et al.*, 1997). Methane emission from irrigated rice was found to be higher in the dry season than in the wet season (Wassman *et al.*, 1993). This is because of higher biomass production and elevated temperature during the periods of high methane emission.

2.2.2.5. Photosynthate partioning and root growth

Methane emission and photosynthetic characteristic of rice are reported to be closely related (Denier van der Gon *et al.*, 2002, Sass and Cicrone, 2002). Carbon is stored in different parts of plant through photosynthesis and through decomposition and root exudation, is incorporated into soil (Jimenez and Lal, 2006; Conrad *et al.*, 2008). On average, 30-60% of the net photosynthetic carbon is allocated to the root, and as much as 40-90% of this fraction enters the soil in the form of rhizo-deposition (Lynch and Whipps, 1990; Marschner, 1996). Experiments utilizing pulse labeling of C revealed that about 1-5% of the net assimilation was incorporated into soil (Lu *et al.*, 2002); a part of which was transported to the rhizosphere, transformed to CH_4, and emitted to the atmosphere (Minoda and Kimura, 1994). It is reported that carbon loss from soils could not be compensated by the carbon input through plant photosynthesis (Zhongjun *et al.*, 2006) The carbon released as CH_4 is approximately equivalent to 3% and 4.5% of photosynthetically fixed carbon in the biomass for low and high emission cultivars, respectively (Huang *et al.*, 2002). The percentage distribution of photosynthetically derived assimilates to soil was exponentially correlated to the rate of root growth (Lu *et al.*, 2002). Greater root growth provides greater surface area for diffusion of CH_4 into roots and greater air space (Singh *et al.*, 1999). Amount of root exudates, which is the primary source of carbon for CH_4 (Weiguo *et al.*, 2006), was reported to be positively correlated to root dry matter production (Wang and Adachi, 2000). Therefore, higher root weight and density increase the CH_4 production and transport (Ladha *et al.*, 1986). Higher amount of CH_4 is produced in soils with rice plants than that of unplanted soil (Zhongjun *et al.*, 2006), which indicates a direct role of rice root

on CH_4 production. Increase in root or aboveground biomass during plant growth until flowering determines the corresponding increase in CH_4 transport capacity (Aulakh *et al.*, 2002). There is an inverse relationship between rice plants' capacity to store photosynthetically fixed carbon and seasonally emitted CH_4 (Sass and Cicerone, 2002) and on average, 11±4% of the carbon not allocated to rice grains was emitted as CH_4 (Denier van der Gon *et al.*, 2002). Weiguo *et al.* (2006) reported that elevated CO_2 significantly increased methane emission (as high as 58%) compared with ambient CO_2. These findings clearly indicate the relationship of photosynthesis and methane emission.

The organic substrate from which the CH_4 is derived presumably comes from root exudation and death (Weiguo *et al.*, 2006). Root exudates play an important role in the process of solubilization and mobilization of nutrients in the soil (Krik *et al*, 1999), and thereby root exudates provide substrates for microbial activity in the rhizosphere. In flooded rice soils, root exudates provide important carbon sources for the process of methanogenesis. Organic acids in root exudates supply energy to methanogens, and also mobilize soil phosphorus and micronutrients (Marschner, 1996). Wang and Adachi (2000) reported that nature and amount of root exudates change with the developmental stages of rice plants. They reported that the exudation rate increases with plant development from seeding to panicle initiation or flowering, but decreases towards the maturity of the crop. It is well documented that plant derived organic carbon can produce 3-4 fold greater amount of CH_4 during panicle initiation to flowering as compared to the seedling stages (Aulakh *et al.*, 2001a). It is therefore suggested that CH_4 production during the later stage of growth of rice plant is determined by plant derived carbon, which is in turn closely associated with the process of photosynthate partioning.

2.2.2.6. Soil and water management

Appropriate field management is one of the important ways to increase grain yield of rice (Minamikawa *et al.*, 2006). Such field management has physical, chemical and biological effects on methane emission. It is reported that average methane flux during the

growing period was affected by fertilizer application, water management, organic matter amendment, water and water management (Yan *et al.*, 2005).

The effect of application of chemical fertilizers on CH_4 emissions is well established (Adhya *et al.*, 2000). The effect of fertilizers on CH_4 production depends on rate, type and mode of applications. For example, application of urea enhances CH_4 production possibly by increasing soil pH following urea hydrolysis and the drop in redox potential, which stimulates methanogenic activities in soil (Wang *et al.*, 1993). Debnath *et al.* (1996) reported that urea along with farm yard manure enhanced methane emission from paddy fields of India. Lindau (1994) reported decrease in CH_4 emission with ammonium nitrate application due to competitive inhibition of nitrate reduction in favour of methane production. Under field conditions, the application of sulphate based fertilizers such as $(NH_4)_2\ SO_4$ and $CaSO_4$ have reduced CH_4 emission (Cai *et al.*, 1997). On the other hand, application of K_2HPO_4 enhances the emission of CH_4 (Adhya *et al.*, 1997). Sulfate containing fertilizers are known to decrease CH_4 emission because of competition between sulfate reducing bacteria and methanogens for the substrates, hydrogen and acetate (Hori *et al.*, 1993). Minamikawa and Sakai (2005) showed that increase in the application of ammonium sulfate decreased CH_4 emission and increased rice yield in field condition. Application of gypsum ($CaSO_4$) is also reported to decrease CH_4 emission (Denier van der Gon and Neue, 1994). It is reported that incorporation of urea into the soil at a depth of 20 cm decreased CH_4 emission to a half of that with surface application (Schutz *et al.*, 1989). Many researchers have showed that CH_4 emission increased with increase in the rate of application of urea (Dannenberg and Conrad, 1999). This was attributed to an increase in soil pH caused by the hydrolysis of urea (Wang *et al.*, 1992), an increase in rice biomass (Banik *et al.*, 1996), and the inhibition of methanotrophs by ammonium (Dubey, 2003). However, some workers reported that ammonium stimulated oxidation of CH_4 (Bodelier *et al.*, 2000). Schimel (2000) suggested that the effects of ammonium on CH_4 oxidation can be arranged into a three-scale phenomenon: stimulation with increases in rice biomass; inhibition with population growth

of methanotrophs on a microbial-community level; and stimulation with competition for CH_4 monooxygenase on a biochemical level.

Water management in paddy field affects the rate of methane emission to a large extent (Kongchum *et. al.*, 2006). Soil submergence and the duration of anaerobiosis strongly determine the rate of CH_4 production (Wassman *et al.*, 2000). Flooding the soil decreases gas diffusion by a factor of more than 10^4, resulting in several changes in soil physico-chemical and biological conditions that favour CH_4 production and its emission (Bharati *et al.*, 2001). On the contrary, free exchange of air under dry-land condition will enhance oxidation of CH_4, a sink process. Non-flooded paddy soils, after drainage or during the fallow period, are able to act as sink for CH_4 and their ability to consume CH_4 vary depending upon the soil temperature or moisture (Thurlow *et al.*, 1995). On a rainfed law-land rice field, CH_4 emission was about 4-10 times higher than that of an irrigated shallow field (Rath *et al.*, 1999). Baruah *et al.* (1997) reported higher methane flux from continuously flooded rice ecosystem than intermittently flooded sandy loam soils of India. Indian alluvial soils also emit less methane from intermittently flooded rice field (Mishra *et al.*, 1997). One or multiple drainage system has been reported to decrease CH_4 emission compared to continuous flooding (Yagi and Minami, 1990). Some workers reported that midseason drainage or intermittent irrigation decreases CH_4 emission without decreasing the rice grain yield (Sass *et al.*, 1992). Submergence with a dry spells during the crop growing period commonly observed in rainfed rice systems is a crucial factor for CH_4 production and emission (Setyanto *et al.*, 2000). Recently, water management base on Eh control has been proposed as an effective mitigation option for methane. This technique maintains soil Eh between predetermined lower and upper limits by drainage and flooding (Minamikawa and Sakai, 2005). Such Eh control reduced CH_4 emission by 64% by regulating water management practices without decreasing rice yield compared to continuous flooding (Minamikawa and Sakai, 2006).

2.2.2.7. Rice cultivars

There are about 80,000 known cultivars of rice with large variations in genotype and phenotype (Jia *et al.*, 2002). Therefore the role of rice cultivars on methane emission has great potential as biological mitigation of methane. Rice cultivars play a significant role in regulating CH_4 emission because of the large variations in morphological and physiological traits which influence CH_4 production rate, rhizospheric CH_4 oxidation and plant mediated CH_4 transport. Varietial difference on methane emission has been reported by many workers (Wang *et al.*, 1997) Since up to 90% of the methane released from rice fields occurs through plant mediated transport mechanism, plant characteristics of rice is reported to have a strong impact on methane emission. Several field studies from China (Kesheng and Zhen, 1997), India (Baruah *et al.*, 2002), Italy (Butterbach-Bahl *et al.*, 1997), and Japan (Watanabe and Kimura, 1995) showed that rice cultivars vary widely in their ability to emit methane. Variations in phenology and physiological characters of rice cultivars are reported to have pronounced effects on methane emission from acids soils of Lower Brahmaputra Valley Zone of Assam (Gogoi *et al.*, 2003; Gogoi *et al.*, 2005). Methane emission and varietal characteristics, such as plant biomass production (Sass *et al.*, 1991), leaf and tiller number (Neue *et al.*, 1996; Mariko *et al.*, 1991; Aulakh *et al.* 2002), root oxidation ability (Satpathy *et al.*, 1998) etc. were found to be closely associated. These findings indicate an ample possibility of selecting rice varieties for lower methane emission.

2.2.2.8. Application of organic manure

It is well known that the application of organic matter conserves soil fertility for sustainable rice production. However, incorporation of organic matter into the soil enhances the supply of substrates for methanogenesis, which in turn increases methane emission. The effect of applied organic matter on methane emission from paddy field depends upon the kind, rate, time, and degree of decomposition in field condition (Minamikawa *et al.*, 2006).

In many rice growing countries, rice straw is applied as a source of organic matter, which is reported to increase CH_4 emission (Schutz *et al.*, 1989). Aerobic decomposition of rice straw of the previous autumn or winter decreased CH4 emission compared to application of straw just before transplanting (Goto *et al.*, 2004). There are several reports on the effect of other kinds of organic matters on methane emission such as *Azolla* (Bharati *et al.*, 2000), wheat straw (Zou *et al.*, 2005) and animal manures (Wang *et al.*, 1999). Such organic matter application also increases CH4 emission from paddy fields.

A low rate of methane emission is generally observed just after transplanting. This is due to the limited carbon sources, low levels of methanogenesis and poor conduction of methane from the soil to the atmosphere through rice plants with under-developed biomass (Satpathy *et al.*, 1997). Some workers reported an initial methane emission maximum that occurs shortly after transplanting. This enhanced emission is caused by the fermentation of easily degradable soil organic matter in the soil (Sass and Fisher, 1992). However, if the amount of easily degradable carbon is low at the beginning of the season, no initial peak of methane emission develops (Neue *et al.*, 1995). It is reported that methane formation during the early and mid-season growth stages of rice, which last for 40 to 50 days in tropical climates, results primarily from microbial decomposition of freshly incorporated crop residues (Wassmann *et al.*, 2000). Therefore, the first methane emission peak, generally observed at active vegetative growth stage of rice, is associated with decomposition of organic matter derived from left over plant residues in the form of paddy straw and dead roots from the previous crop, which served as substrate for methanogens (Xu *et al.*, 2000). The second highest CH_4 flux maxima, commonly recorded during the panicle initiation stage, were attributed to the higher availability of organic substrates in the rice rhizosphere (Mitra *et al.*, 2005). Lu *et al.* (2000) also established a similar trend and reported that the seasonal change in methane emission was closely related to the change in organic carbon concentration in the root zone. Although, CH_4 production is negligible in soils under non-flooded conditions (Ramakrishnan *et al.*, 1995), soils with high organic matter can also serve as a source for CH_4 in non-flooded condition (Rath *et al.*, 1999).

2.3. Methane emission from rice fields: Global and Indian scenario

The total annual global emission of methane is estimated to be 420-620 Tg y^{-1} (Khalil and Rasmussen, 1990), 70-80% of which is biogenic in origin (Bouwman, 1990). Agricultural activities are responsible for approximately 50% of global atmospheric inputs of methane (Scheehle and Kruger, 2006; USEPA, 2006). Rice paddies have been identified as one of the major sources of atmospheric CH_4, contributing about 10-15% to global CH_4 emissions (Neue, 1993; Scheehle and Kruger, 2006). The human population continues to increase by about 80 million people per year; the developing world will add another two billion people over the next three decades (Cohen, 2003). Therefore it has been suggested that the world's annual rice production must increase from 518 million tonnes in 1990 to 760 millions in 2020 (IRRI, 1989). This would require expansion and intensification of rice cultivation, and as a consequence it is likely that CH_4 fluxes will increase to the atmosphere Some researchers estimated annual emission of methane from rice paddies ranging between 47 and 60 Tg yr^{-1}, representing 8.5- 10.9% of total emission from all sources (Crutzen, 1995; Houghton *et al.*, 1995). Estimates of regional methane emissions from rice paddies differ largely, depending on the techniques, approaches and databases used for extrapolation. Over the past few decades, numerous field experiments identified the magnitude, temporal pattern and influencing factors of CH_4 emissions from paddy fields (Nouchi *et al.* 1994; Denier van der Gon and Neue, 1995). Worldwide methane emission from rice has been estimated from reports from China, India, Vietnam, Korea, and the Philippines to be from 21 to 30 Tg per year (Sass *et al.* 2002). Minami (1994) proposed a methodology for estimating global CH_4 emission from rice fields and reported a CH_4 emission range of 10 to 113 Tg CH_4 per year from world rice paddy fields. Ghosh *et al.* (1995) estimated the upper limit of global methane production from paddy fields as 13 Tg, based on the reports on total biomass of globally produced rice.

Most of the CH_4 emitted from rice fields is expected to be from the Asian region as it has 90% of the total world rice harvested area, out of which about 52% is in China and

India (Bachelet and Neue, 1993). A review of CH_4 studies in China, India, Japan, Thailand, the Philippines and the USA (Sass and Fisher Jr, 1994) tightened the range of projected CH_4 emissions from rice fields. Sass and Fisher Jr (1994) combined the data of total area of rice paddies with the flux estimates obtained from several investigations (Minami *et al.*, 1994). According to this estimation, annual methane emission (Tg Yr^{-1}) from the paddy fields of China , India, Japan, Thailand, Philippines, USA, and other countries were 13-17, 2.4-6, 0.02-1.04, 0.5-8.8, 0.3-0.7, 0.04-0.50 and 9.20-20.0 Tg respectively (Mimami, 1997). The rice area in the countries shown in this estimate represent 63% of the total world rice paddy area and result in a total annual CH_4 emission of 16 to 34 Tg. Extrapolating these data to the world, Sass and Fisher Jr (1994) estimates total CH_4 emission from rice fields to range between 25.4 and 54 Tg with 50 Tg per year as a possible global emission value. This value is near the IPCC (1992) best estimate of 60 Tg CH_4 per year, but the range indicates that the actual rate may be lower. Wang *et al.* (1994) estimate the annual CH_4 emission from rice in China to range between 13-17 Tg per year. However, Lin *et al.* (1995) estimate a slightly lower value from rice in China of <12 Tg CH_4 per year.

A national methane measurement campaign in India yielded a range of CH_4 flux values between 0.20 and 3.6 mg m^{-2} h^{-1} for irrigated, intermittently- flooded rice fields, 0.04-66 mg m^{-2} h^{-1} for flooded fields and between 1.1 and 23.3 mg m^{-2} h^{-1} for deep-water regimes (Parashar *et al.*, 1994). Parashar *et al.* (1994a) estimated CH_4 emission from India's paddy at 3 Tg yr^{-1}; however this estimate was based on a limited number of field measurements. Recently, Bhatia *et al.* (2004) used IPCC default flux values for the base year 1994-95 to estimate CH_4 emissions from all agricultural fields in India to arrive at a figure of 2.9 Tg CH_4 yr^{-1}. Great efforts have been made to measure methane emissions from different rice cropping systems in recent years and numerous data from field measurements and laboratory incubations have been accumulated. Recently, the Denitrification and Decomposition (DNDC) model was evaluated for its ability to simulate methane(CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions from Indian rice fields with various management practices (Pathak *et al.*, 2005). They projected that continuous flooding of rice fields (42.25

million ha) will result 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 will reduce 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 will be increased to 0.05–0.06 Tg N_2O-N. The GWP, however, will be reduced to 91.73-211.80 Tg CO_2 equivalent.

Chapter 3

Materials and Methods

3. MATERIALS AND METHODS

In the present investigation, experiments were carried out at North Bank Plain Agroclimatic Zone (NBPAZ) of Assam, a state of north-east India. The details of materials and methods employed during the course of the investigation are described below.

3.1. Association of plant growth parameters with methane emission from monsoon / *Sali* rice

This experiment was conducted over two consecutive years (2005 and 2006) at NBPAZ of Assam with two (2) rice varieties during monsoon season under rainfed condition (monsoon / *Sali* rice agroecosystem). The detail technical programme of this experiment is given below.

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

In this agroclimatic zone, rice is the major crop grown both under irrigated and unirrigated condition. This experiment was conducted in a farmer's field at Amolapam near Tezpur Central University campus (26°41′ N, 92°50′ E) during the monsoon rice-growing season (August-November of 2005 and 2006). Figure 3.1 shows the geographical location of the experimental site located at the NBPAZ, northeast India. The region is subtropical humid having moderately hot-wet summers and dry winters. The available meteorological data during the experimental periods were collected and are presented in Figure 3.2 and 3.3. The Agroclimatic Zone is characterized by light textured loamy alluvial

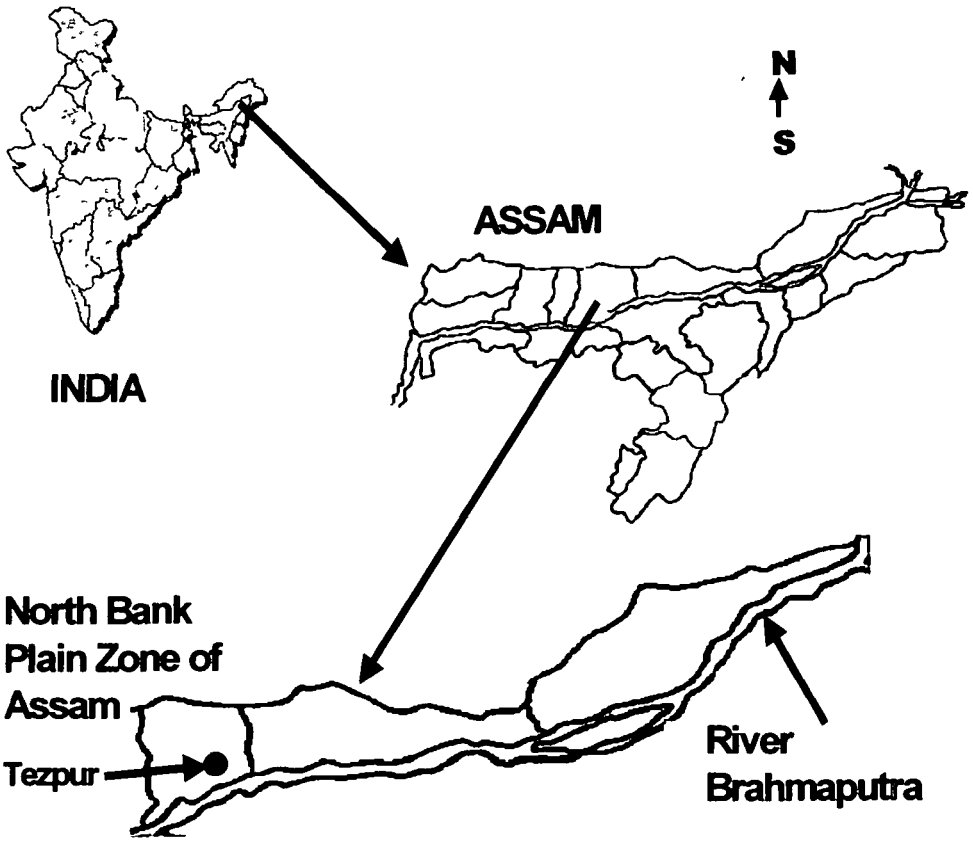


Fig. 3.1. Experimental site at North Bank Plain Agroclimatic Zone (NBPAZ) of Assam, northeast India.

soils. Various soil physiochemical properties of the experimental field are presented in Table 3.1. Light intensity above and below the canopy of rice plant was measured by a light meter (LI 250A, LI-COR, USA) and light transmission (%) through the canopy of rice plant is presented in Figure 3.4.

3.1.2. Selection of rice variety

Two high yielding rice varieties *viz.* Bahadur and Piolee were selected for the experiment.

3.1.2.2. Description of varieties

1. Bahadur: 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 variety recommended for shallow water (0-30 cm) agroecosystem for monsoon (*Sali*) season. Duration and average yield in ideal field condition is 150-155days and 5.0-5.5 t ha^{-1}, respectively.

2. Piolee: It 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 variety, having very good grain quality. It is recommended for shallow water (0-30 cm) agroecosystem for monsoon (*Sali*) season Duration and average yield in ideal field condition is 150-155days and 5.0-5.5 t ha^{-1}, respectively.

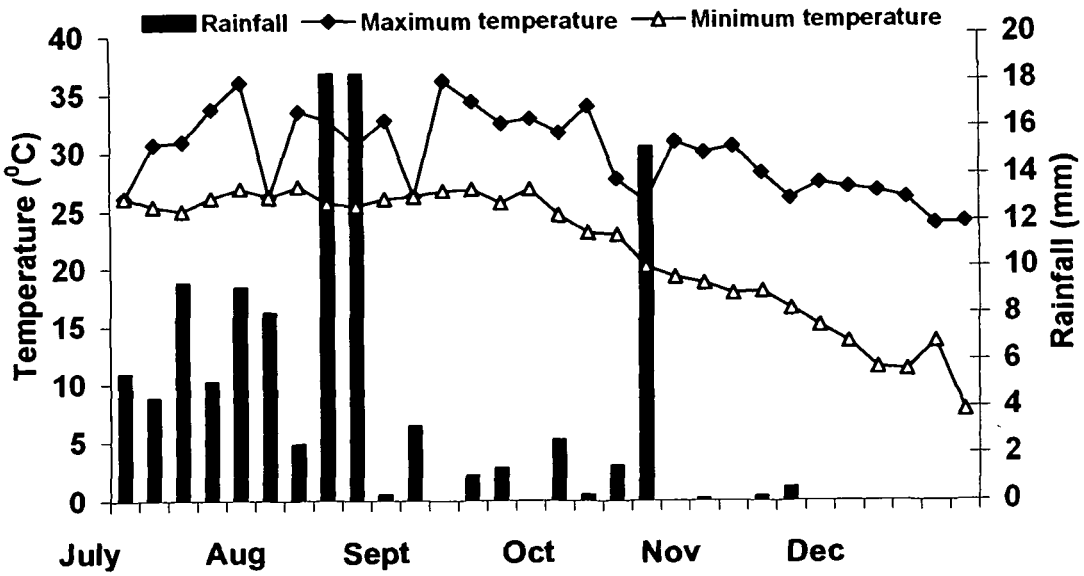


Fig. 3.2. Meteorological parameters during the experimental period of 2005 (*Sali* season).

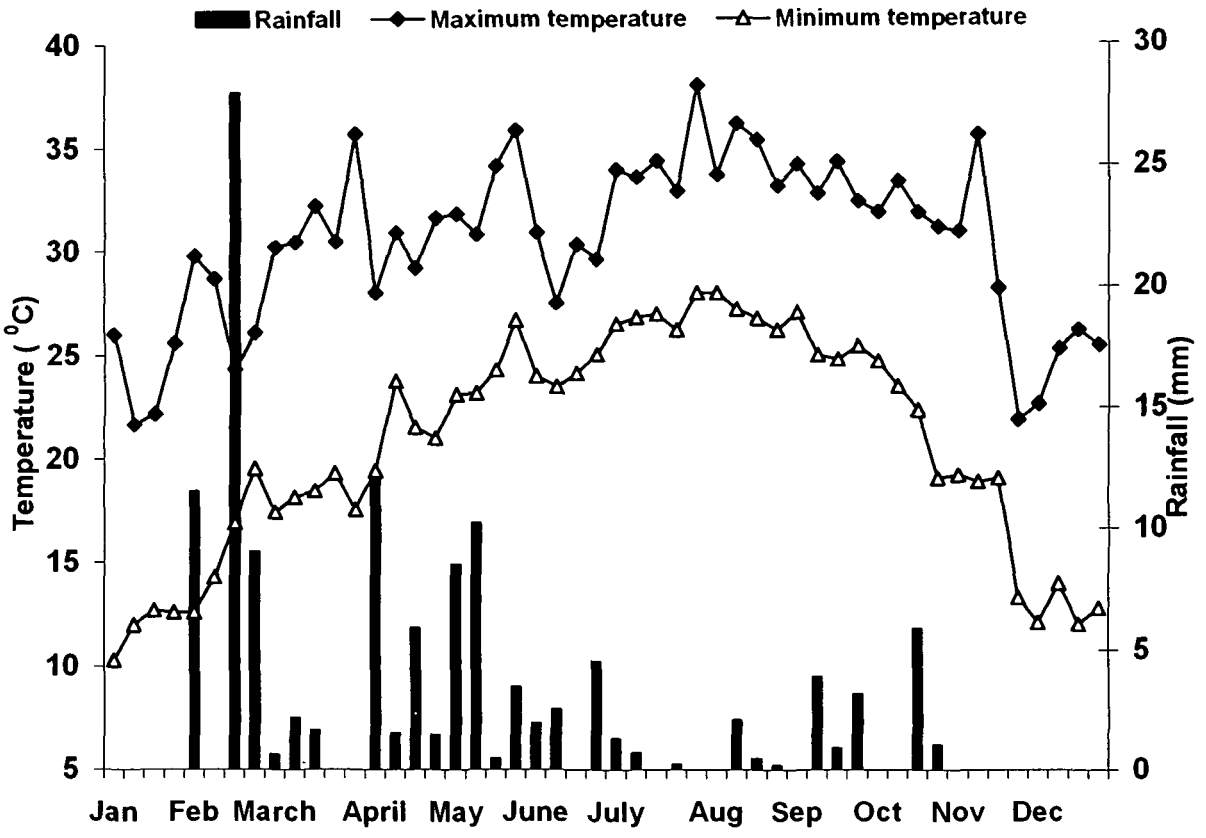


Fig. 3.3. Meteorological parameters during the experimental period of 2006 (*Boro, Ahu* and *Sali* season).

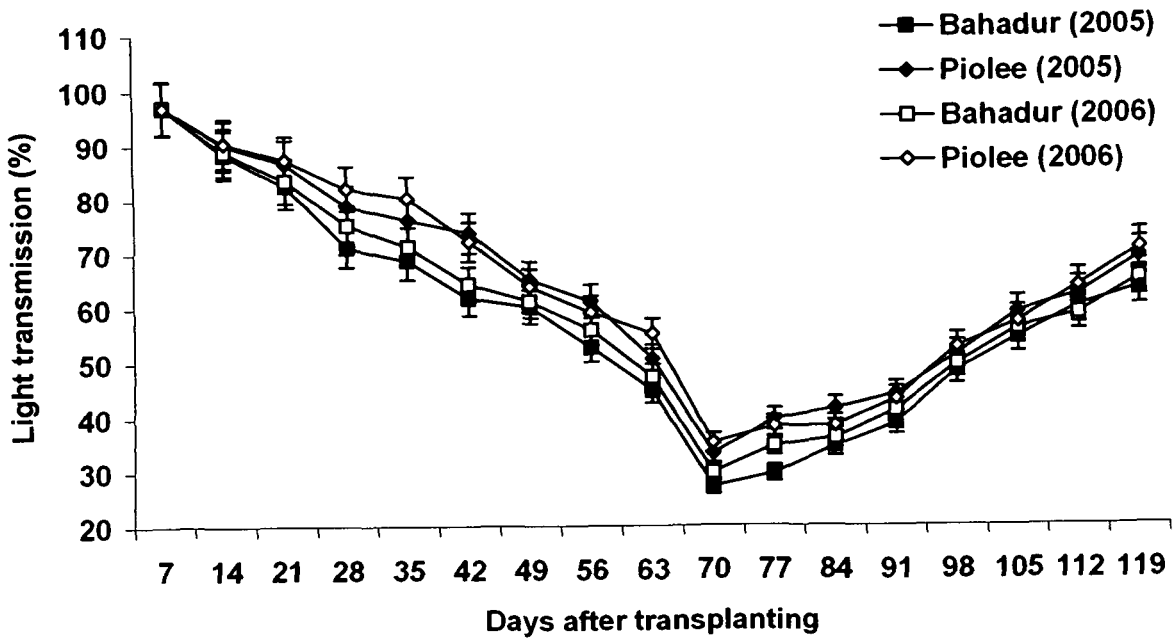


Fig. 3.4. Light transmission (%) through the canopy of varieties Bahadur and Piolee. Data presented are means ± SEd (vertical bars).

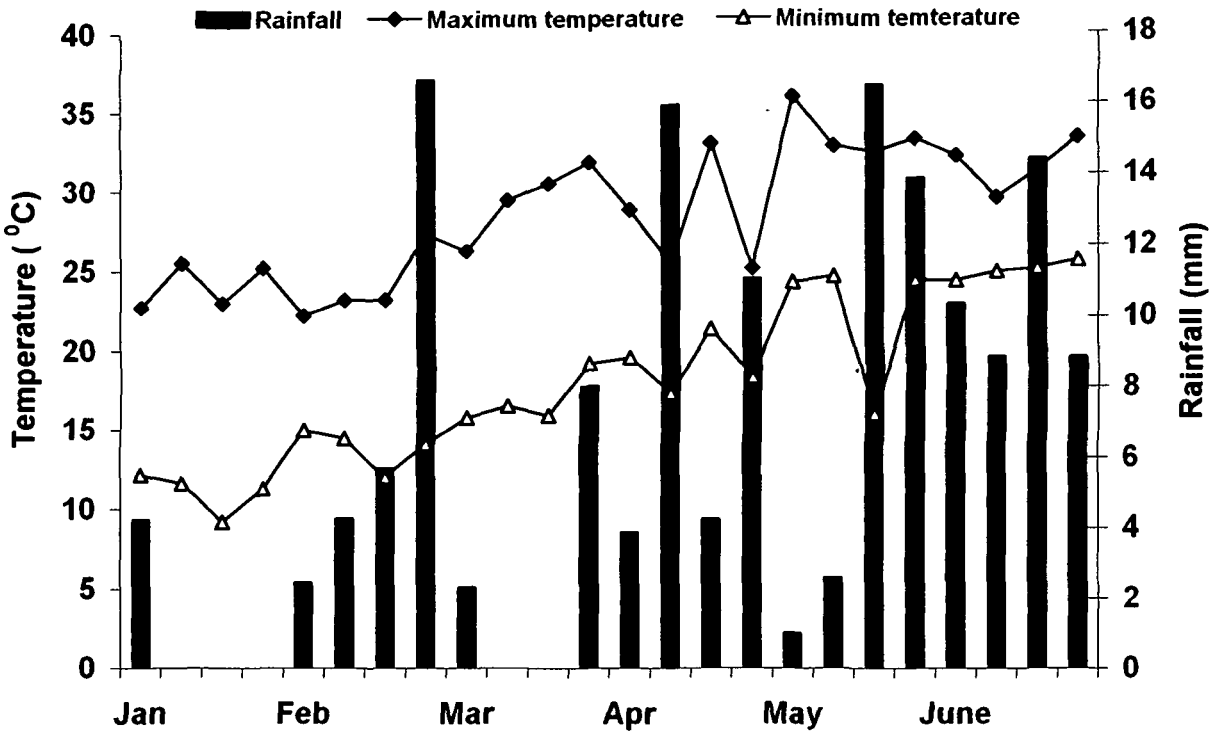


Fig. 3.5. Meteorological parameters during the experimental period of 2007 (*Boro* season).

3.1.3. Field preparation

The experimental plot was ploughed, puddled thoroughly to 15-cm depth and levelled. Fertilizer was applied at the rate of 40: 20: 20 kg N-P-K ha^{-1} in the form of urea, single super phosphate (SSP) and murate of potash (MOP). One third ($1/3^{rd}$) of full dose of urea along with full dose of SSP and MOP was applied at the time of final land preparation. Remaining part of urea was applied at the time of tillering (1/2 of the remaining part) and panicle initiation stage (another 1/2 of the remaining part), as recommended in the package of practice of Assam Agricultural University. Rice seedlings (25-day old) of two varieties, *viz.* Bahadur and Piolee were transplanted (spacing: 20cm x 20 cm; 2 seedling per hill) in four replicated plots (5 x 5m = 25 m^2).

3.1.4. Gas sampling and estimation of methane emission

Methane flux from rice field was recorded at seven (7) different growth stages *viz.* early tillering (42 DAT: Days after transplanting), late tillering (56 DAT), panicle initiation (70 DAT), flowering (84 DAT), grain development (98 DAT), ripening (112 DAT) and maturation (119DAT). Two additional methane samplings were done at 7 and 14 days after harvest. Methane flux was recorded by using a static chamber technique(Plate 3.1) described by Parashar *et al.* (1996). Briefly, chambers 50 cm long, 30 cm wide and 70 cm tall made of 6-mm-thick clear acrylic sheet were used for gas sampling. Rectangular U shaped aluminium channel (50 cm X 30 cm) supported on an aluminium frame (50 cm X 30 cm X 15 cm) was used to support the chambers. The aluminium channels were inserted into the soil to a depth of 15 cm 7 days before transplanting. During gas sampling, the aluminium channels were filled with water to a depth of 2.5 cm. This acted as an air seal for the flux boxes. A battery-operated fan inside each box thoroughly mixed the air in the chamber before sampling. Gas samples were drawn from the chambers using a 50 ml airtight syringe fitted with a three-way stop-cock and a fine needle that was inserted through a self-sealing rubber septum. Gas

samples were collected at intervals of 15 min at 09-00h for four times and again at 14-00 h. During each sampling, temperature and water level inside the chamber were measured. Atmospheric pressure was also recorded at the time of gas sampling. This permitted calculation of air volumes at standard temperature and pressure (STP). Soil temperature was measured with the help of soil thermometer inserted in to the soil near the chamber (at 5cm distance) at the time of sampling. The average of morning and evening values (°C) were considered as the soil temperature value for the day.

Methane in gas samples was determined (Plate 3.2) using a gas chromatograph (Varian, Model 3800, The Netherlands) fitted with flame ionization detector (FID) and Chromopack capillary column (50 cm long, 0.1μm inside diameter). Column, injector and detector temperature were maintained at 50, 90 and 150 ^{0}C respectively. Gas chromatograph was calibrated with a methane standard (5.5ppm) obtained from National Physical Laboratory, New Delhi. Nitrogen, hydrogen and zero air was used as carrier gas, fuel gas and supporting gas respectively. Methane flux was calculated from the temporal increase in the CH_4 concentration inside the box using the equation of Parashar *et al.* (1996):

$$Flux = \frac{BV_{STP} \times C_{CH_4} \times 16 \times 1000 \times 60}{10^6 \times 22400 \times A \times t} mgm^{-2}h^{-1}$$

Where, BV_{STP} is the box air volume in C.C. at STP. It was calculated by :

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

BV (Box air volume) was calculated by:

BV = [(H - h) LW - biomass volume inside box]

Where,

H = Box height (cm)

h = Water level above the channel (cm)

L = Box length (cm)

W = Box width (cm)

BP = Barometric pressure (mm Hg)

T = Box air temperature at the time of sampling (°C)

C_{CH4}= Change in CH_4 concentration in ppmv from 0 to t min. and

A = Paddy area covered by the box (m^2)

The average of morning and evening fluxes were considered as the flux value for the day.

3.1.5. *Morpho-physiological parameters of plant*

3.1.5.1. Plant height

Plant height was measured at weekly interval in cm from the base of the plant to the end of the top leaf with the help of a scale. The average plant height of ten samples from each variety was taken and expressed as plant height (cm $plant^{-1}$).

3.1.5.2. Leaf number per hill

Number of leaves per hill was counted at weekly interval. The average leaf number of ten hills from each variety were taken and expressed as leaf number $hill^{-1}$.

3.1.5.3. Tiller number per hill

Total number of tillers including the main shoot was counted at weekly interval. The average tiller number of ten hills from each variety were taken and expressed as tiller number hill^{-1}.

3.1.5.4. Leaf area per hill

Leaf area per hill was measured at weekly interval with a portable laser leaf area meter (Plate 3.3) (CID, Model CI-203). The average leaf area of ten hills from each variety were taken and expressed as leaf area (cm^2 hill^{-1}).

3.1.5.5. Leaf area index

Leaf area index was measured at weekly interval using the following formula:

$$\text{Leaf area index (LAI)} = \frac{\text{Leaf area (cm}^2\text{)}}{\text{Ground area (cm}^2\text{)}}$$

3.1.5.6. Root length and volume

Total root length per hill was measured at weekly interval by a portable laser leaf area meter (CID, Model CI-203) with root measurement attachment. The average root length of ten hills from each variety 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 variety were taken and expressed as root volume (ml $hill^{-1}$).

3.1.5.7. Culm, leaf blade, leaf sheath and root dry weight

Root and shoot portion from ten hills were collected separately from each variety at weekly interval. The shoot portion was carefully separated into culm, leaf blade and leaf sheath The root portion was washed thoroughly to remove the soil and sand particles under running water over a sieve. Appropriate care was taken so that the minute parts of roots can be collected. Both root and shoot parts were oven dried at 75^0C till the weight become constant. The average culm, leaf blade, leaf sheath and root dry weight of ten hills from each variety were taken and expressed as dry weight (g $hill^{-1}$).

3.1.5.8. Leaf photosynthetic rate

Leaf photosynthesis was measured at weekly interval (from 7 days after transplanting till harvest) by an infra-red gas analyzer (LI-6400 portable photosynthesis system, LICOR, USA), under ambient environmental conditions (Plate 3.4). The photosynthetic rate (μ mol CO_2 m^{-2} s^{-1}) of intake leaf was measured following the method of Baig *et al.* (1998). The middle portion of a fully expanded, healthy-green 2^{nd} leaf from the top was used for measurement up to the pre-flowering stage, and the flag leaf was used for photosynthesis measurement from the panicle initiation stage of the crop. Leaves were held in the chamber until values of photosynthesis were observed to be as constant as possible (steady state). Leaves were kept at steady state for 1 min before measurements were taken.

3.1.6. Yield and yield attributing parameters

3.1.6.1. Thousand-grain weight

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

3.1.6.2. Panicle length

Panicle length was measured from the nodal base of the panicle to the tallest part of the main rachis. Average length of panicles from ten plants of each variety was taken and expressed as panicle length (cm).

3.1.6.3. Dry weight of developing panicle

After panicle initiation, the developing panicles were collected separately from each variety at weekly interval and were oven dried at 75^0C till the weight became constant. The average dry weight of developing panicle from ten hills were taken and expressed as dry weight (g $hill^{-1}$).

3.1.6.4. Filled grain

Filled grains were separated from the unfilled grains by soaking them in water. The percentage was worked out to get the filled grain %. The average filled grain of ten samples from each variety were taken and expressed as filled grain (%).

3.1.6.5. Yield

The mature plants were harvested from one square meter area from each plot avoiding the border rows. After threshing and cleaning, the grain yield was recorded. Values presented here are average of four replications and expressed as tone hectare^{-1}.

3.1.7. Soil physico-chemical properties

Soil samples were collected from the root zone of rice plants from 15cm depth from the four replicate plots with the help of a soil-sampling core and composite samples were prepared from the collected soils. Root fragments were removed carefully from the soil and various physico-chemical properties were analyzed.

3.1.7.1. Soil pH

On each methane flux measurement day, soil pH was measured at 1:1.25 soil to water ratio (soil water slurry) using a digital pH meter.

3.1.7.2. Cation exchange capacity

Soil samples were collected from the experimental field before the start of the experiment. The cation exchange capacity (CEC) of the soil samples were determined by 1N ammonium acetate (pH 7.0) method (Jackson, 1973).

3.1.7.3. Determination of clay, sand and silt content

Soil samples collected from the experimental field before the start of the experiment were analyzed for clay, silt and sand fraction by employing Buyoucous hydrometer method (Black, 1965).

3.1.7.4. Soil organic carbon

Organic carbon content of the soils was determined at weekly interval on each methane flux measurement day by standard wet oxidation method. One gram of soil sample was treated with ten (10) ml of 1 N potassium dichromate and 20ml of concentrated H_2SO_4 was added in the solution. After 30 minutes, 200ml of water, 10 ml of 1N phosphoric acid and 1ml of diphenylamine indicator was added. The solution turned bluish purple in colour. This was titrated against 0.5N standard ferrous ammonium sulphate solution till the contents become grayish green in colour. Simultaneously, a blank determination was also conducted and the value was recorded. The organic carbon was calculated by the method of Walky and Black (Jackson, 1973).

3.1.7.5. Soil nutrient content

Estimation of soil nitrogen content was carried out by Micro Kjeldahal method (Jackson, 1973). Potassium and phosphorus content of soils were estimated by Flame photometric method and Colorimetric method (Jackson, 1973), respectively. 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

Measurements of different parameters for all the growth stages were replicated for four times. The significance or non-significance of a given variance was determined by calculating the respective 't' and SE ± values (Gomez and Gomez, 1984), considering the variety as source of variation. Correlation of methane flux with other parameters (means of all different growth stages) was done by Pearson correlation method.

3.2. Association of plant growth parameters with methane emission from irrigated / *Boro* rice

This experiment was conducted at irrigated rice agroecosystem of NBPAZ of Assam with two (2) rice cultivars during spring season (*Boro* rice) under irrigated condition. The detail technical programmes of this experiment are given below.

Table 3.1. Soil characteristics of the experimental fields of different agroecosystems.

Parameters	Year / Cropping season				
	Sali		*Ahu*	*Boro*	
	2005	2006	2006	2006	2007
pH	5.43 ± 0.02 [a]	5.36 ± 0.01 [a]	5.40 ± 0.06[a]	5.45 ± 0.01 [a]	5.36 ± 0.01 [a]
EC (mmhos/100g)	0.47 ± 0.02	0.45 ± 0.01	0.43 ± 0.02	0.47 ± 0.01	0.45 ± 0.02
CEC (m eq. $100g^{-1}$)	9.54 ± 0.23	9.31 ± 0.43	10.20 ± 0.55	10.87 ± 0.15	10.13 ± 0.15
Bulk density (g cc^{-1})	0.66 ± 0.01	0.66 ± 0.02	0.85 ± 0.02	0.87 ± 0.01	0.85 ± 0.01
Clay (%)	28.60 ± 0.23	28.53 ± 0.56	30.10 ± 0.49	31.57 ± 0.12	32.43 ± 0.18
Silt (%)	41.15 ± 0.28	41.38 ± 0.53	41.40 ± 0.90	39.50 ± 0.21	40.27 ± 0.09
Sand (%)	30.25 ± 0.43	30.10 ± 0.55	28.50 ± 0.44	28.93 ± 0.09	27.30 ± 0.15
Organic carbon (%)	0.93 ± 0.01	0.97 ± 0.01	0.94 ± 0.01	0.95 ± 0.01	0.96 ± 0.01
Available Nitrogen (kg ha^{-1})	373.13 ± 1.03	375.38 ± 2.07	375.40 ± 1.73	378.67 ± 1.62	371.50 ± 1.27
Available Phosphorus (kg ha^{-1})	35.50 ± 0.79	37.00 ± 0.79	36.20 ± 0.83	39.43 ± 0.64	36.83 ± 0.70
Available Potassium (kg ha^{-1})	234.63 ± 1.16	238.13 ± 1.21	237.70 ± 2.03	240.90 ± 0.81	236.3 0± 0.70
Total Iron (ppm)	448.00 ± 1.78	454.00 ± 2.08	445.00 ± 2.08	431.00 ± 2.65	438.67 ± 0.67
Total Manganese (ppm)	20.75 ± 0.85	22.25 ± 0.85	20.00 ± 1.00	19.67 ± 0.88	23.00 ± 2.08
Total Copper (ppm)	17.75 ± 0.85	19.75 ± 0.85	17.00 ± 1.53	17.67 ± 1.45	20.33 ± 1.20
Total Zinc (ppm)	25.50 ± 1.26	26.00 ± 0.82	23.00 ± 1.53	24.00 ± 1.53	22.33 ± 1.45

[a] = Standard error

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

The geographical location and climatic conditions of the experimental area are described in 3.1.1. The experiment was conducted over two consecutive years (2006 and 2007) in a farmer's field at Amolapam near Tezpur Central University campus (26°41′ N, 92°50′ E) during the spring rice-growing season (February- June). The available meteorological data of the experimental periods were collected and are presented in Figure 3.3 and 3.5. The experimental site comprises light textured loamy alluvial soils. Soil samples were collected from the experimental field before the start of each experiment and analyzed. Various soil physiochemical properties of the experimental field are presented in Table 3.1. Light transmission (%) through the canopy of rice plant is presented in Figure 3.6.

3.2.2. Selection of rice variety

Two rice varieties *viz.* Ranjit and Agni were selected for this experiment.

3.2.2.2. Description of varieties

1. Ranjit: This variety was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, India, by cross combination between 'Pankaj' and 'Mahsuri'. This semi-dwarf variety is recommended for shallow water (0-30 cm) agroecosystem. It is also grown under irrigated condition. Duration and average yield in ideal control field condition is 150-155days and 5.0-5.5 t ha^{-1} respectively.

2. Agni: It is an indigenous traditional rice cultivar, generally grown under irrigated condition during *Boro* season.

3.2.3. Field preparation

The experimental plot was ploughed, puddled thoroughly to 15-cm depth and levelled. Fertilizer was applied at the rate of 60: 30: 30 kg N-P-K ha^{-1} in the form of urea, single super phosphate (SSP) and murate of potash (MOP). One third ($1/3^{rd}$) of full dose of urea along with full dose of SSP and MOP was applied at the time of final land preparation. Remaining part of urea was applied at the time of tillering (1/2 of the remaining part) and panicle initiation stage (another 1/2 of the remaining part), as recommended in the package of practice of Assam Agricultural University. Thirty-five days old rice seedlings (5-6 leaf stage) of cultivars Agni and Ranjit were transplanted (spacing: 20cm x 20 cm; 2 seedling per hill) in four replicated plots (5 x 5m = 25 m^2). Fields were submerged by applying irrigation from transplanting to panicle initiation (70 DAT) stage of the crop.

3.2.4. Gas sampling and estimation of methane emission

Methane flux was recorded from the first day of transplanting (0 DAT) and thereafter 7-day intervals till harvest. Two additional methane samplings were done at 7 and 14 days after harvest. Details of materials and methods employed are described in 3.1.4. Cumulative methane emissions from rice varieties for the entire growth period were computed by the method of Naser *et al.* (2007) by using the following formula:

$$\text{Cumulative gas emission} = {}^{n-1}\Sigma_{i=1} / (R_i \text{ X } D_i),$$

Where, R_i is the mean gas emission (mg m^{-2} day^{-1}) of the two sampling times, D_i is the number of days in the sampling interval, and n is the number of sampling times. Cumulative methane emissions are expressed as seasonal integrated flux (E_{sif}) in g m^{-2}.

3.2.5. *Morpho-physiological parameters of plant*

Details of the methodology employed for the determination of morpho-phisyological parameters of plants are described in 3.1.5.

3.2.6. Yield and yield attributing parameters

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

3.2.8. Statistical analysis

Details of the method of statistical analysis are described in 3.1.8.

3.3. Association of plant growth parameters with methane emission from rainfed upland / *Ahu* rice

This experiment was conducted at rainfed rice agroecosystem of North Bank Plain Zone of Assam with two (2) rice varieties during summer season (*Ahu* rice). The detail technical programme of this experiment is given below.

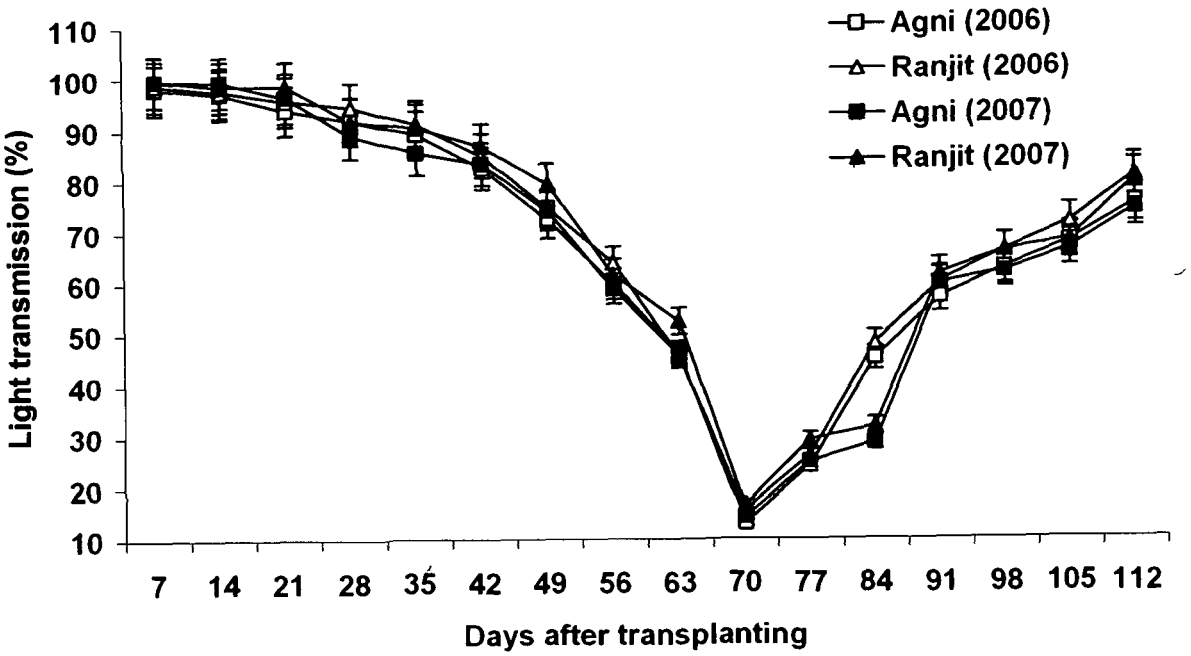


Fig. 3.6. Light transmission (%) through the canopy of cultivars Agni and Ranjit. Data presented are means ± SEd (vertical bars).

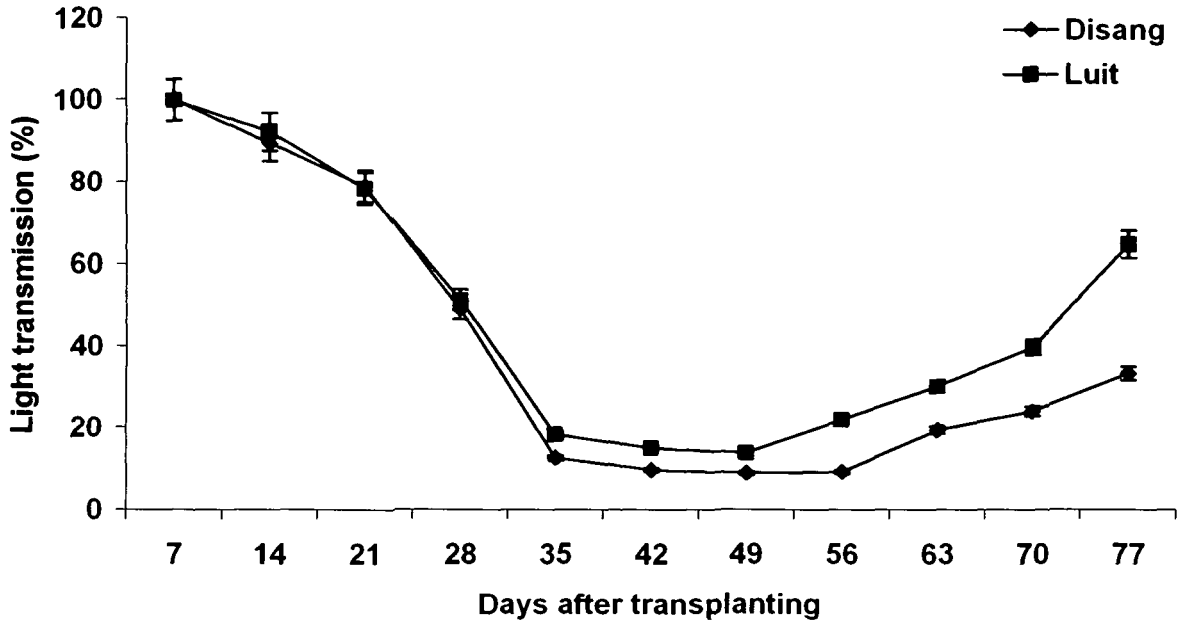


Fig. 3.7. Light transmission (%) through the canopy of varieties Disang and Luit. Data presented are means ± SEd (vertical bars).

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

The geographical location and climatic conditions of the experimental area are described in 3.1.1. Methane emission from paddy fields was estimated during the rainfed summer rice (locally known as *Ahu*) growing season (April - July) of 2006. The available meteorological data during the experimental periods were collected and presented in Figure 3.3. Various soil physiochemical properties of the experimental field are presented in Table 3.1. Light transmission (%) through the canopy of rice plant is presented in Figure 3.7.

3.3.2. Selection of rice variety

Two rice varieties *viz.* Disang and Luit were selected for this experiment.

3.3.2.2. Description of varieties

1. Disang: 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 semi-dwarf variety is recommended for flood-prone areas before the onset of flood in *Ahu* season. Duration and average yield in field condition is 95-100 days and 3.5-4.0 t ha^{-1} respectively.

2. Luit: This variety was developed at Regional Agricultural Research Station (RARS), Titabor of Assam Agricultural University, Jorhat, India, by cross combination between 'Heera' and 'Annada'. It is recommended for flood-prone areas in *Ahu* season (April-July). Duration and average yield in ideal field condition is 95-100 days and 3.5-4.0 t ha^{-1} respectively.

3.3.3. Field preparation

The methodology of field preparation is described in 3.1.3.

3.3.4. Gas sampling and estimation of methane emission

Methane flux was recorded from the day of transplanting at 7-days intervals. Two additional methane samplings were done at 7 and 14 days after harvest. Details of materials and methods employed are described in 3.1.4. Cumulative methane emissions from two rice varieties for the entire growth period were computed as described in 3.2.4.

3.3.5. *Morpho-physiological parameters of plant*

Details of the methodology employed for the determination of morpho-physiological parameters of plant are described in 3.1.5.

3.3.6. Yield and yield attributing parameters

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

3.3.8. Statistical analysis

Details of the methods of statistical analysis are described in 3.1.8.

3.4. Analysis of intervarietal difference in methane flux from rice plants grown during monsoon season as biological mitigation option

This experiment was conducted at shallow water rice agroecosystem of North Bank Plain Zone of Assam with ten (10) rice cultivars during monsoon season (*Sali* rice). The detail technical programme of this experiment is given below.

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

The geographical location and climatic conditions of the experimental area are described in 3.1.1. Methane emission from paddy fields was estimated during the rainfed monsoon rice (locally known as *Sali*) growing season (August - November) of 2006. The available meteorological data during the experimental periods were collected and presented in Figure 3.3. Various soil physicochemical properties of the experimental field are presented in Table 3.1. Light transmission (%) through the canopy of rice plant is presented in Figure 3.8.

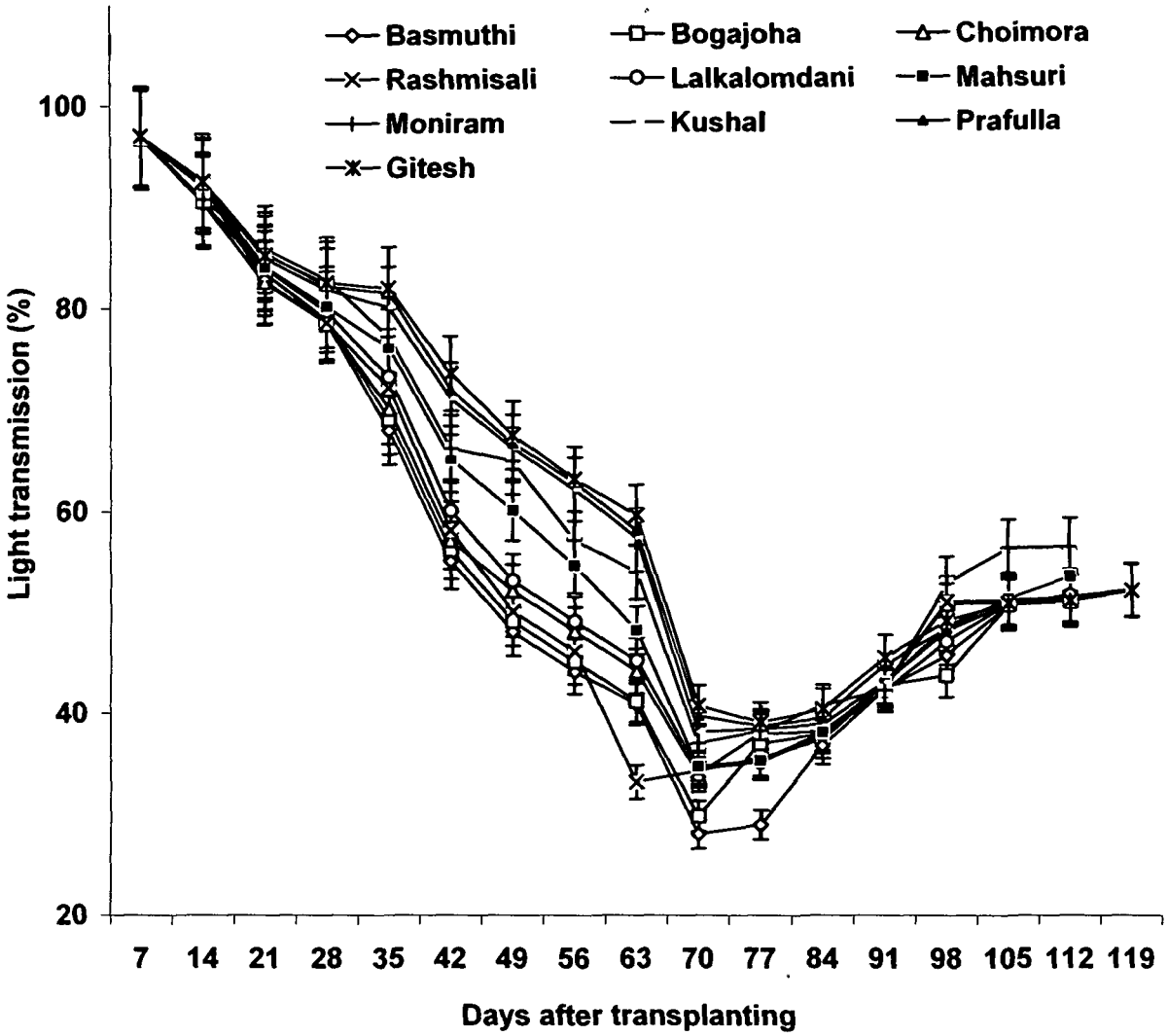


Fig. 3.8. Light transmission (%) through the canopy of ten rice cultivars. Data presented are means ± SEd (vertical bars).

3.4.2. Selection of rice variety

This experiment was conducted with ten (10) rice cultivars. Among the cultivars, five (5) were traditional rice genotypes popularly grown in this agro-climatic zone, *viz.* Basmuthi (V_1), Bogajoha (V_2), Choimora (V_3), Rashmisali (V_4) and Lalkalomdani (V_5); and the other five (5) were high yielding varieties *viz.* Mahsuri (V_6), Moniram (V_7), Kushal (V_8), Prafulla (V_9) and Gitesh (V_{10}).

3.4.2.2. Description of varieties

1. Basmuthi (V_1): It is an indigenous tall traditional rice cultivar. It is grown under rainfed low-land condition during monsoon (*Sali*) season.

2. Bogajoha (V_2): It is an indigenous traditional rice cultivar. It is generally grown under rainfed low-land condition during monsoon (*Sali*) season. This tall cultivar has good cooking quality.

3. Choimora (V_3): It is also an indigenous traditional rice cultivar. It is grown under rainfed low-land condition during monsoon (*Sali*) season.

4. Rashmisali (V_4): It is an ndigenous traditional rice cultivar. It is generally grown under rainfed low-land condition during monsoon (*Sali*) season.

5. Lalkalomdani (V_5): This is also a local collection. It is a popular traditional cultivar of the agroclimatic zone. This cultivar has good cooking quality and is grown during monsoon season.

6. Mahsuri (V_6): It is a derivative of Indica and Japonica hybridization programme. The cross combination was between Taichung 65 and Mayong ebos 80/2. It has medium slender grain type with very good cooking quality. Duration and average yield in ideal field condition is 140-145 days and 3.5-4.0 t ha^{-1} respectively.

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'. This semi-dwarf variety is recommended for shallow water (0-30cm) submergence in flood prone areas. It is a blast tolerant non-lodging variety. Duration and average yield in ideal control field condition is 150-155 days and 4.5-5.0 t ha^{-1} respectively.

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'. This semi-dwarf variety is recommended for shallow water (0-30cm) submergence in flood prone areas. It is a non-lodging variety. Duration and average yield in ideal control field condition is 150-155 days and 4.5-5.0 t ha^{-1} respectively.

9. Prafulla (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. Duration and average yield in ideal control field condition is 150-155 days and 5.0-5.5 t ha^{-1} respectively.

10. Gitesh (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. Duration and average yield in ideal control field condition is 150-155 days and 5.0-5.5 t ha^{-1} respectively.

3.4.3. Field preparation

The experimental plot was ploughed, puddled thoroughly to 15-cm depth and levelled. Fertilizer was applied at the rate of 40: 20: 20 kg N-P-K ha^{-1} in the form of urea, single super phosphate (SSP) and murate of potash (MOP). One third ($1/3^{rd}$) of full dose of urea along with full dose of SSP and MOP was applied at the time of final land preparation. Remaining part of urea was applied at the time of tillering (1/2 of the remaining part) and panicle initiation stage (another 1/2 of the remaining part), as recommended in the package

of practice of Assam Agricultural University. Rice seedlings (25-day-old) of ten rice cultivars were transplanted (spacing: 20cm x 20 cm; 2 seedling per hill) in four replicated plots (5 x 5m = 25 m^2).

3.4.4. Gas sampling and estimation of methane emission

Methane flux was recorded from the first day of transplanting (0 DAT) and thereafter at 7-days intervals till harvest. Two additional methane samplings were done at 7 and 14 days after harvest Details of materials and methods employed are described in 3.1.4. Cumulative methane emissions from two rice varieties for the entire growth period were computed as described in 3.2.4.

3.4.5. *Morpho-physiological parameters of plant*

Transpirational rates (mmol H_2O m^{-2} sec^{-1}) of intake leaf were measured at weekly interval (from 7 DAT till harvest) by an infra-red gas analyzer (LI-6400 portable photosynthesis system, LICOR, USA), under ambient environmental conditions. The middle portion of a fully expanded, healthy-green 2^{nd} leaf from the top was used for measurement up to the pre-flowering stage, and the flag leaf was used for transpiration measurement from the panicle initiation stage of the crop. Leaves were held in the chamber until values of transpiration were observed to be as constant as possible (steady state). Leaves were kept at steady state for 1 min before measurements were taken.

Details of the methodology employed for the determination of other morpho-physiological parameters of plant are described in 3.1.5.

3.4.6. *Leaf and stem anatomy*

For scanning electron microscopic (SEM) analysis, leaf sections were prepared from the middle portion of the flag leaf at panicle initiation stage. Nodal sections of the stems were taken from about 15 cm above the ground surface Fresh leaf and stem samples of different rice cultivars were fixed and dehydrated following the method of Neinhuis and Edelmann (1996). After fixation and dehydration samples were fixed to metal stubs with carbon adhesive tape, coated with platinum by Auto Fine Coater (JEOL, JFC-1600) and examined in a Scanning Electron Microscope (JEOL, JSM-6390LV, Japan). Observations and photographs with the scanning electron microscope were made at 15KV. Stomatal frequency was measured from four random fields of each sample (from adaxial surface) and mean values are expressed as number of stomata mm^{-2}. For the measurement of the diameter of medullary cavity, stem sections were taken from the rice plants from about 15cm above the ground surface. Leaf sheaths were carefully removed and fine sections of the culm were examined under Stereo Microscope (Stemi 2000-C, ZEISS, Germany) at 40 X. Observations were recorded from four microscopic fields of each sample and diameters of medullary cavity (mm) were computed by using Axiovision LE Documentation Software (Germany).

3.4.7. Yield and yield attributing parameters

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

3.4.8. Soil physico-chemical properties

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

3.4.9. Statistical analysis

Measurements of different parameters at all the growth stages were replicated for four times. The significance of the difference was assessed by ANOVA and subsequently by Duncan's multiple range test (DMRT), and differences are reported at probability (P) <0.05, considering cultivars as source of variation. Correlations of physiological and anatomical parameters (mean values of different growth stages) with mean CH_4 flux values from the cultivars were done by using SPSS package programme (Version 10.0).

Plate 3.1. Gas sampling in rice field by static chambers

Plate 3.2. Gas-sample analysis in Gas Chromatograph

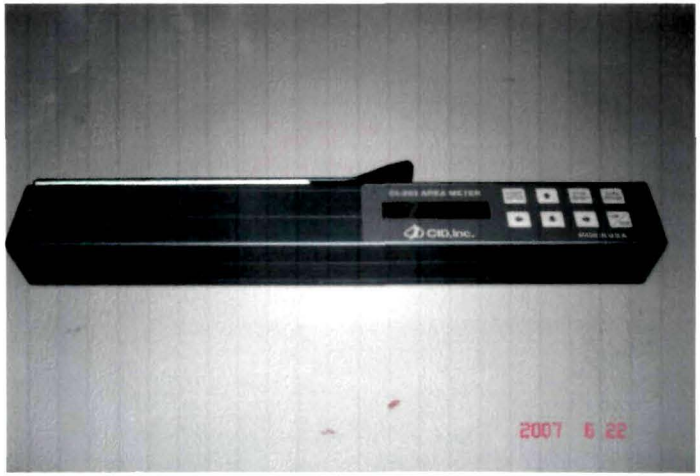


Plate 3.3. Portable laser leaf area meter

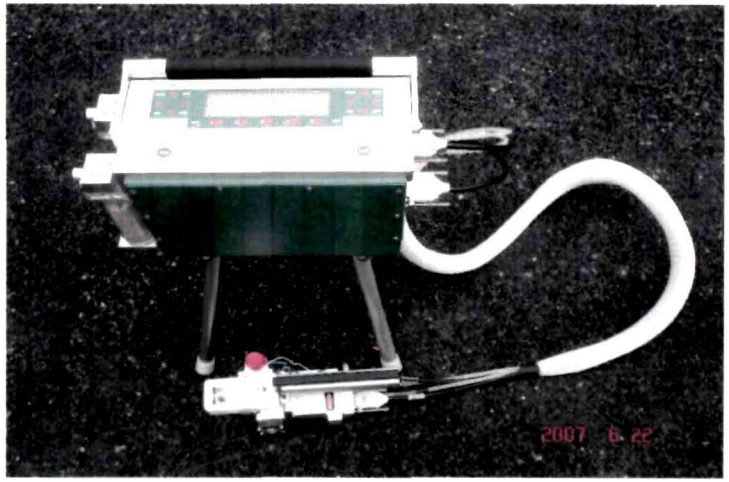


Plate 3.4. Portable photosynthesis system

Chapter 4

Results

4. RESULTS

Results obtained from the present investigation on methane emission from paddy fields are presented with figures and tables and are described below.

4.1. Association of plant growth parameters with methane emission from monsoon / *Sali* rice

4.1.1. Meteorological parameters

Figure 3.2 and 3.3 represents the meteorological parameters i.e. rainfall (mm) and air temperature (maximum and minimum) in ^{0}C at weekly interval of the crop-growing season. In both the years, during the initial stage of the crop growing period (August- September) higher temperatures were recorded, and towards the end of the crop growing season (October- November), gradual drop in temperatures was observed. Higher amount of rainfall was recorded in the year 2005 compared to 2006.

4.1.2. Methane flux (mg CH_4 m^{-2} hr^{-1})

Two-years of measurement of methane flux from Bahadur and Piolee grown in rainfed condition for two consecutive years (2005 and 2006) exhibited cultivar differences in its emission (Fig. 4.1). Methane flux from rice field was recorded at different growth stages *viz.* early tillering (42 DAT), late tillering (56 DAT), panicle initiation (70 DAT), flowering (84 DAT), grain development (98 DAT), ripening (112 DAT) and maturation (119DAT) Two additional methane samplings were done after the crop was harvested. Higher flux was recorded for variety Bahadur compared to variety Piolee in both the years. Methane flux

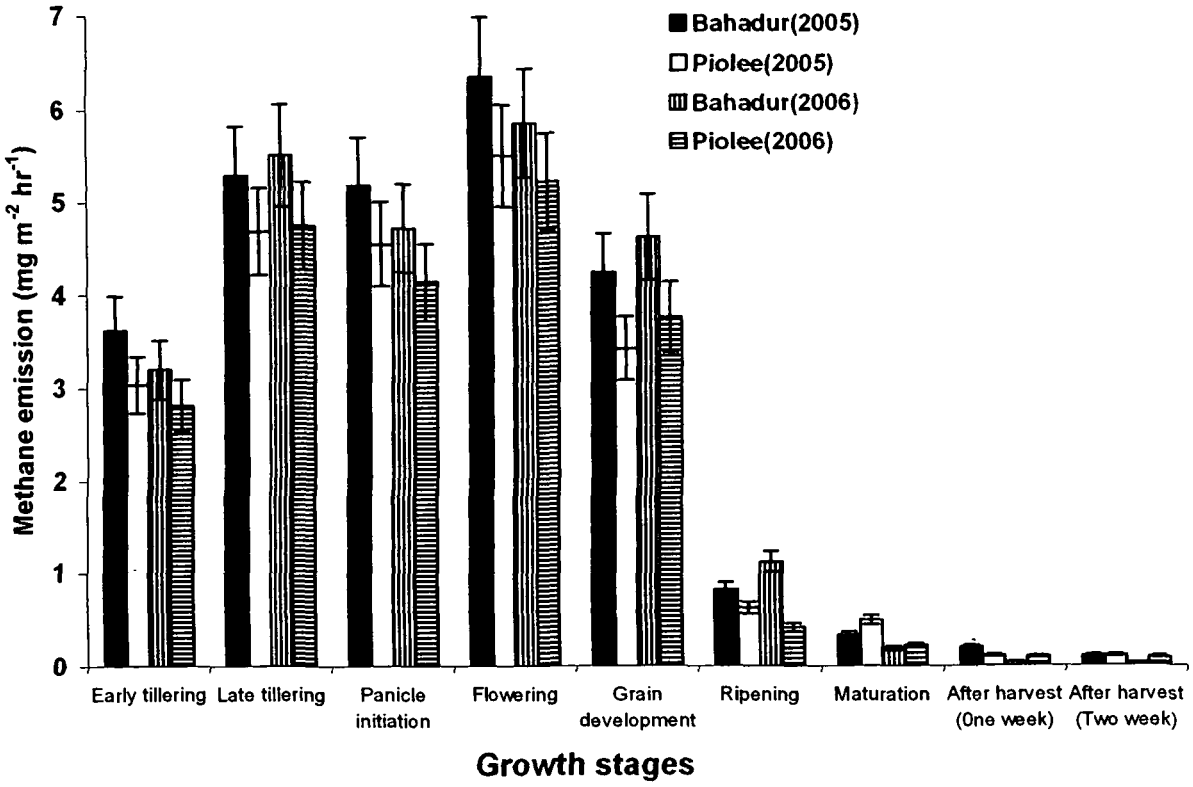
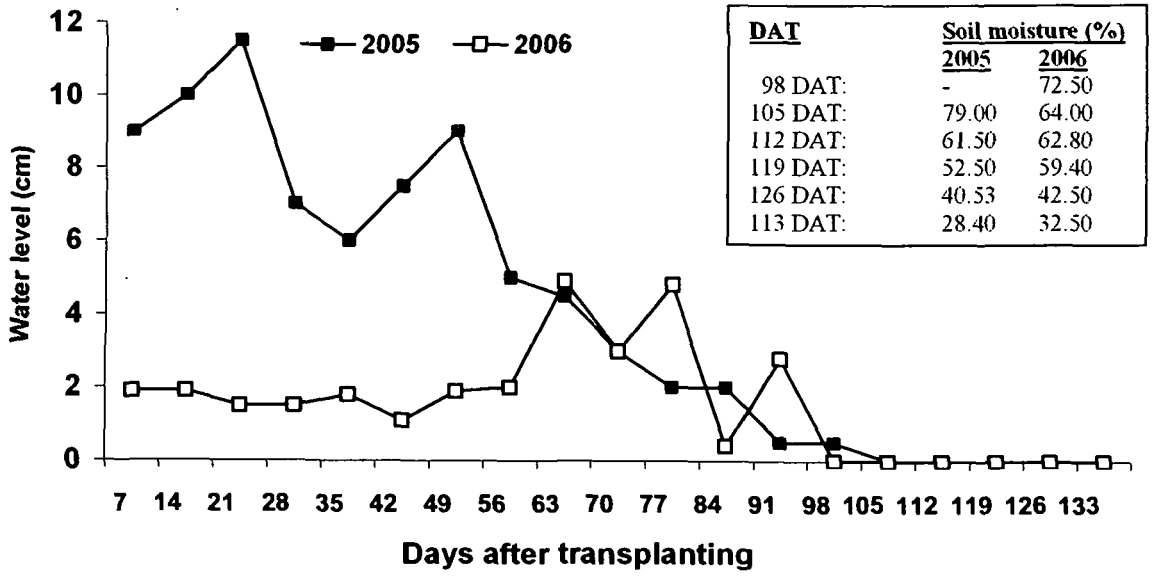


Fig. 4.1. Methane emission (mg m^{-2} hr^{-1}) from varieties Bahadur and Piolee at different growth stages. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).



DAT	Soil moisture (%)	
	2005	2006
98 DAT:	-	72.50
105 DAT:	79.00	64.00
112 DAT:	61.50	62.80
119 DAT:	52.50	59.40
126 DAT:	40.53	42.50
113 DAT:	28.40	32.50

Fig. 4.2. Water level (cm) of the experimental field planted with varieties Bahadur and Piolee.

was highest at flowering stage (in 2005, 6.33mg CH_4 m^{-2} hr^{-1} in Bahadur and 5.48mg CH_4 m^{-2} hr^{-1} in Piolee and in 2006 it was 5.83mg CH_4 m^{-2} hr^{-1} in Bahadur and 5.20mg CH_4 m^{-2} hr^{-1} in Piolee) followed by late tillering (2005: 5.28mg CH_4 m^{-2} hr^{-1} in Bahadur and 4.68mg CH_4 m^{-2} hr^{-1} in Piolee; 2006: 5.50mg CH_4 m^{-2} hr^{-1} in Bahadur and 4.74mg CH_4 m^{-2} hr^{-1} in Piolee), panicle initiation (2005: 5.17mg CH_4 m^{-2} hr^{-1} in Bahadur and 4.54mg CH_4 m^{-2} hr^{-1} in Piolee; 2006: 4.71mg CH_4 m^{-2} hr^{-1} in Bahadur and 4.13mg CH_4 m^{-2} hr^{-1} in Piolee) and grain development(2005: 4.22mg CH_4 m^{-2} hr^{-1} in Bahadur and 3.41mg CH_4 m^{-2} hr^{-1} in Piolee; 2006: 4.60mg CH_4 m^{-2} hr^{-1} in Bahadur and 3.74mg CH_4 m^{-2} hr^{-1} in Piolee) stage of the crop. Effect of growth stage on methane emission was similar in both the years irrespective of varieties. Decline in methane emission in the varieties was observed during grain development and found to be minimum at maturity (Fig. 4.1). Methane emission was negligible after harvest of the crop.

4.1.3. Water level (cm)

Water level (cm) in the experimental field was recorded at every week and results are presented in Figure 4.2. Seasonal rainfall kept the experimental field submerged during crop growth period in both the years (up to 105 DAT in 2005 and 98 DAT in 2006). The field water level attained the highest value at 21DAT (11.5cm) and 63DAT (4.9cm) in the year 2005 and 2006, respectively.

4.1.4. Soil organic carbon (%)

Organic carbon content (%) of the soil planted with the rice varieties was initially low, but increased at late tillering and flowering stage (Fig. 4.3) of the crop. Similar trend was observed in the soils grown with the varieties in the other experimental years. Higher soil organic carbon was recorded in the fields planted with Bahadur compared to Piolee. Soil

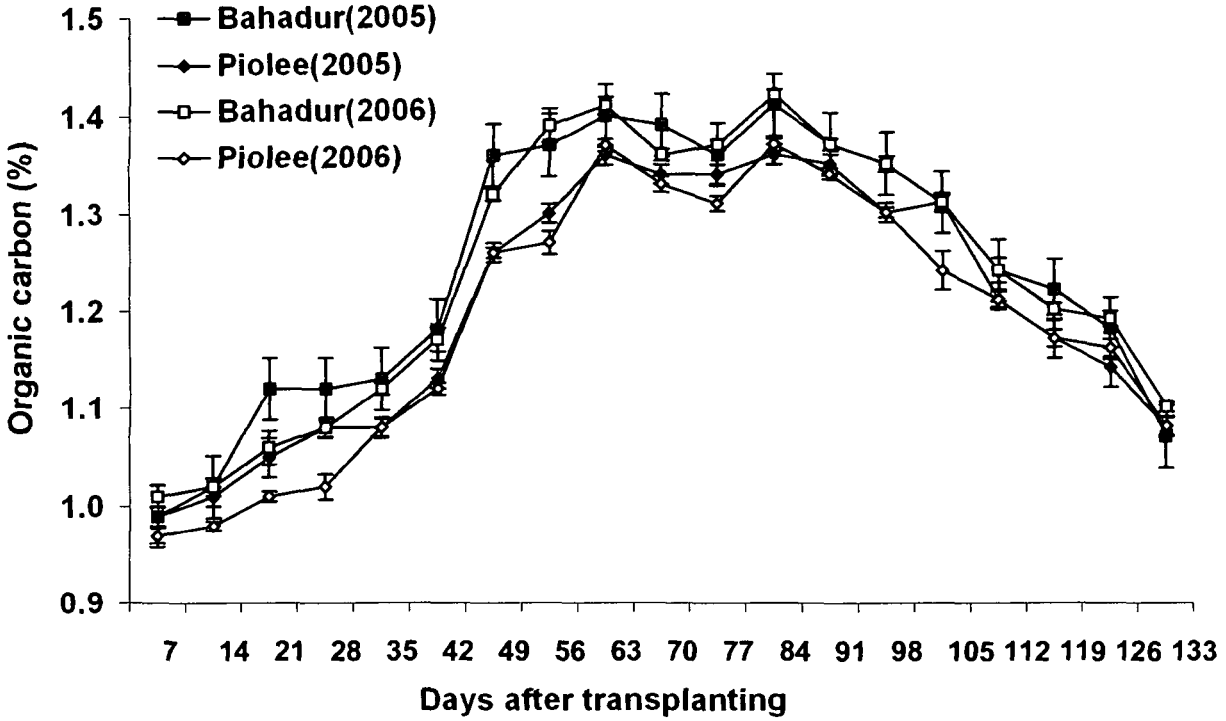


Fig. 4.3. Organic carbon (%) of the experimental field planted with varieties Bahadur and Piolee. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

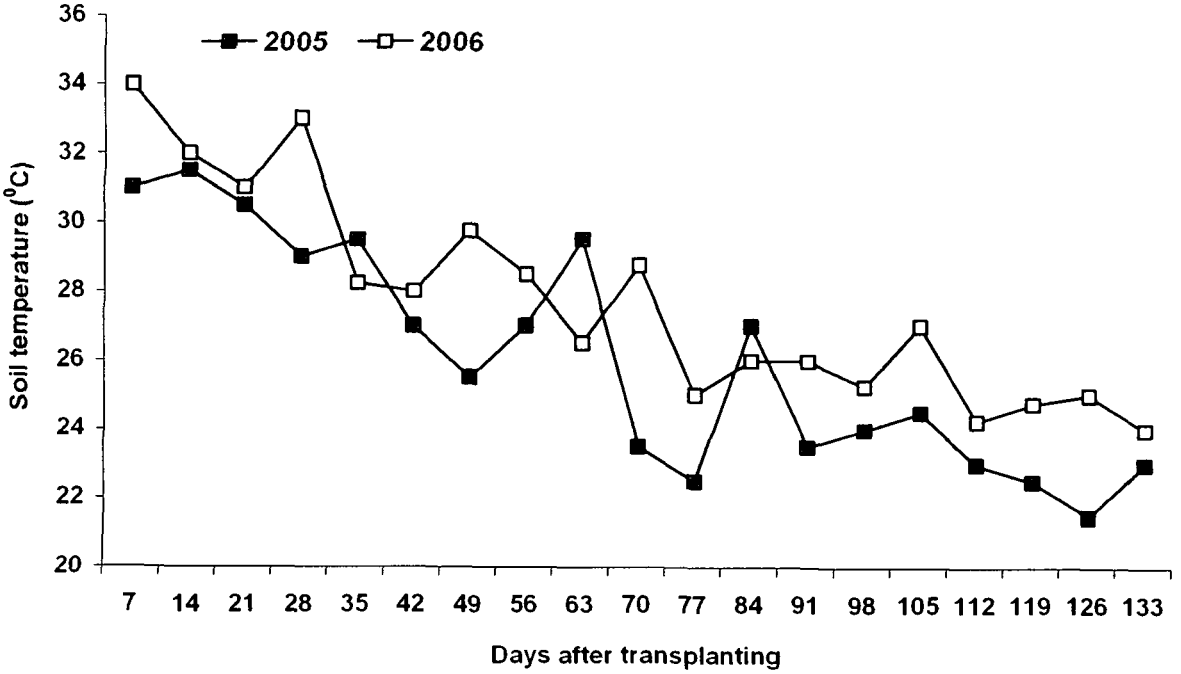


Fig. 4.4. Soil temperature (^{0}C) of the experimental field planted with varieties Bahadur and Piolee.

organic carbon (%) was highest at 63 DAT (1.4% in Bahadur and 1.36% in Piolee during 2005 and during 2006, 1.41% in Bahadur and 1.37% in Piolee) and 84 DAT (1.41% in Bahadur and 1.36% in Piolee during 2005 and 1.42% in Bahadur and 1.37% in Piolee during 2006). Highly significant positive correlation was found between methane emission and soil organic carbon content (Table 4.4).

4.1.5. Soil temperature (°C)

Figure 4.4 represents the soil temperatures (°C) of the experimental fields. Soil temperatures of the experimental fields were recorded at weekly interval from 7 DAT till 14 days after harvest. Higher soil temperature was observed during the initial stage of crop growth (2005: 31.50°C at 14 DAT; 2006: 34.0°C at 7 DAT). Soil temperatures started to decrease gradually along with the growth of the crop and reached lower values during crop maturation stage in both the years. The recorded high soil temperature on 63 DAT and 84 DAT during 2005 was due to higher ambient temperature of 32 °C and 29 °C respectively. Similarly, higher soil temperature on 28 DAT, 49 DAT, 70 DAT and 105 DAT during 2006 was also due to higher ambient temperature recorded on those days 34 °C, 33 °C, 32 °C and 28 °C, respectively.

4.1.6. Soil pH

Figure 4.5 represents the soil pH measured at weekly interval from 7 DAT to two weeks after harvest. In 2005, the recorded soil pH was 5.37 at 7 DAT which started to increase up to 63 DAT and reached 6.34 and then there was a decreasing trend till harvest in the fields planted with Bahadur. In 2006, pH increased from 5.40 (7DAT) to 6.33 (56 DAT) and then decreased in the fields planted with Bahadur. Fluctuation of soil pH in the plots

with Piolee was also of similar nature like Bahadur with a variation from 5.39 (7 DAT) to 6.37 (63 DAT) in 2005, and 5.44 (7 DAT) to 6.37 (56 DAT) in 2006, respectively.

4.1.7. Plant height (cm)

Plant height (cm) was recorded at weekly interval starting from 7 DAT till harvest (Table 4.1). Variation in plant height was observed in both the varieties. In 2005, rapid increase in plant height was recorded up to 84 DAT in both Bahadur (84.40cm) and Piolee (78.55cm). Although there was increase in plant height in the varieties, but the increment in height was at a slower rate from 84 DAT onward. In 2006, rapid increase in plant height was recorded up to 77 DAT in both Bahadur (83.09cm) and Piolee (75.60cm). In both the years, Bahadur recorded significantly higher plant height compared to Piolee.

4.1.8. Leaf number (hill^{-1})

Table 4.1 represents the leaf number per hill of the varieties Bahadur and Piolee. In 2005, at initial stage (7 DAT), the recorded leaf numbers were 31 and 24 hill^{-1} in variety Bahadur and Piolee respectively, which increased gradually up to 83 hill^{-1} in Bahadur and 73 hill $^{-1}$ in Piolee at 77 DAT. Subsequently, decrease in leaf number was noticed due to senescence and abscission of older leaves in both the varieties. In 2006, the recorded leaf numbers were 26 and 21 hill^{-1} in variety Bahadur and Piolee respectively at 7DAT, which increased up to 79 hill^{-1} in Bahadur and 71 hill $^{-1}$ in Piolee at 77 DAT. Bahadur recorded significantly higher leaf number compared to Piolee in both the years.

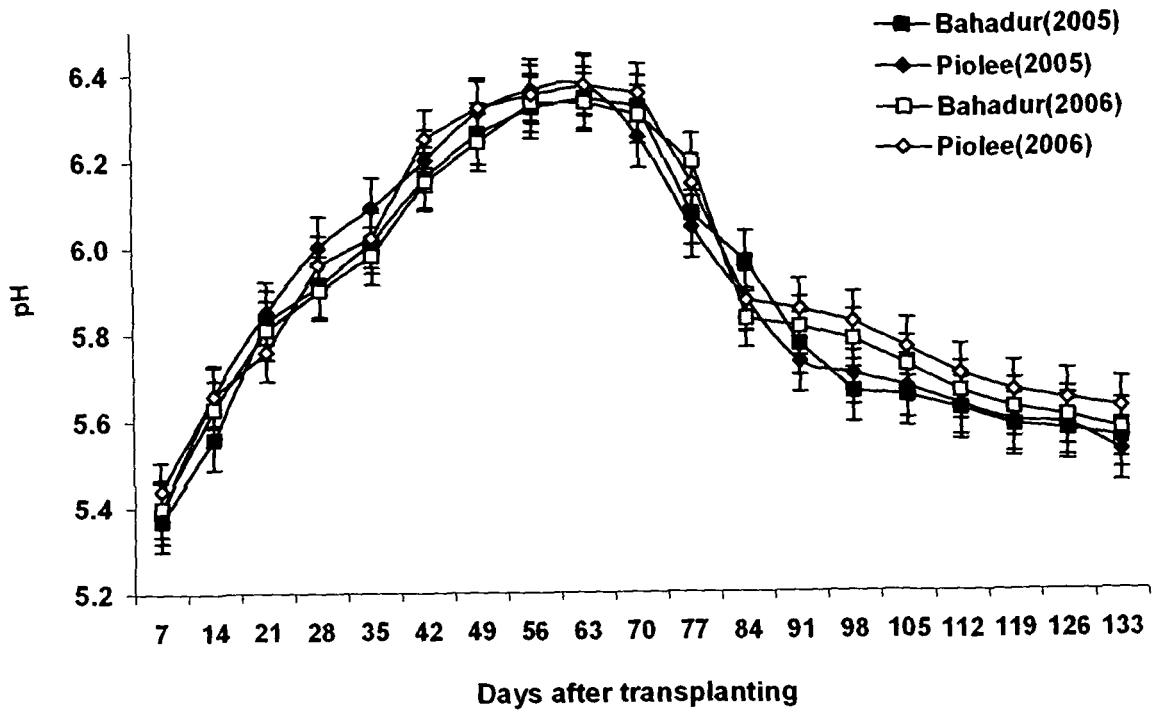


Fig. 4.5. Soil pH of the experimental field (varieties Bahadur and Piolee). Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

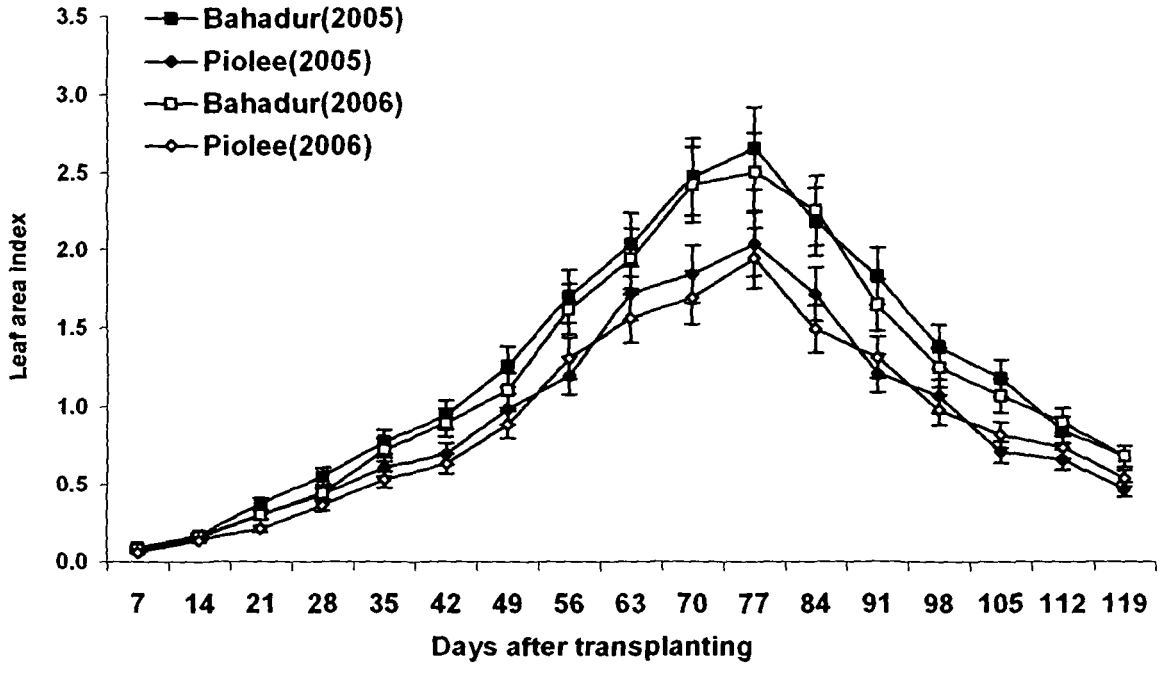


Fig. 4.6. Leaf area index of varieties Bahadur and Piolee. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

Table 4.1. Comparison of growth parameters (plant height, leaf number, leaf area and tiller number hill^{-1}) between varieties Bahadur and Piolee grown in monsoon / *Sali* ecosystem.

		Days after transplanting																
		7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119
Plant height (cm)	2005																	
	Bahadur	36 80**	42 20*	48 40**	53 50**	56 20**	62 70**	68 20**	71 30*	76 20**	78 30*	81 50**	84 40*	85 30*	86 10*	87 00**	87 30**	87 8**
	Piolee	29 55**	35 75*	39 55**	46 85**	48 85**	55 15**	59 65**	65 45*	68 35**	72 05*	73 85**	78 55*	79 15*	80 15*	80 35**	80 55**	80 65**
	t values	4 13	3 67	5 04	3 78	4 18	4 30	4 87	3 33	4 47	3 56	4 35	3 33	3 50	3 39	3 78	3 84	4 07
	2006																	
	Bahadur	35 32**	43 47**	46 55**	51 67**	57 44**	60 86**	65 63**	70 10**	73 15**	77 57**	83 09**	83 49**	83 84**	84 25**	84 52**	84 70**	84 89**
	Piolee	28 00**	38 40**	40 68**	45 29**	49 58**	53 09**	57 92**	62 83**	66 15**	68 77**	75 6**	76 57**	76 91**	77 18**	77 45**	77 69**	77 81**
	t values	18 49	17 50	17 67	18 45	8 09	14 50	16 03	15 46	15 89	24 15	16 20	12 28	13 01	12 08	12 38	12 26	12 34
Leaf number (hill^{-1})	2005																	
	Bahadur	31 50*	45 00*	51 00*	53 50*	60 75*	67 00**	69 50*	75 50*	76 25*	79 00*	83 50**	76 25**	37 75*	29 50^{NS}	27 25^{NS}	26 25^{NS}	25 75^{NS}
	Piolee	24 25*	39 25*	45 75*	48 00*	54 00*	55 75**	62 75*	67 25*	68 75*	71 00*	73 75**	62 25**	33 75*	27 25^{NS}	26 25^{NS}	25 50^{NS}	25 25^{NS}
	t values	2 64	2 52	2 84	2 52	2 96	4 94	2 87	2 96	3 08	3 33	4 23	5 74	3 05	1 10	0 40	0 29	0 21
	2006																	
	Bahadur	26 28**	45 10**	47 63**	53 03**	58 18**	63 30**	67 58**	71 90**	74 70**	77 83**	78 55**	67 03**	29 70^{NS}	26 60**	25 53**	25 08**	24 68**
	Piolee	20 53**	40 85**	44 20**	49 03**	51 73**	56 45**	60 73**	64 35**	67 15**	69 30**	71 13**	59 00**	28 70^{NS}	25 35**	24 73**	24 38**	24 18**
	t values	19 11	9 32	4 67	4 90	9 43	9 20	8 90	8 80	8 64	10 18	9 77	44 90	2 21	5 06	5 44	6 81	8 02
Leaf area(cm^2) (hill^{-1})	2005																	
	Bahadur	37 99^{NS}	68 45^{NS}	149 62**	221 40**	309 86**	377 92**	500 91**	674 7**	808 92**	979 70**	1052 79**	864 66**	723 23**	548 13**	469 31**	335 00**	269 76*
	Piolee	29 35^{NS}	61 42^{NS}	119 86**	173 79**	245 87**	277 74**	391 22**	474 30**	683 97**	731 42**	806 29**	681 83**	479 26**	423 38**	281 82**	260 47**	185 24*
	t values	2 40	1 95	8 26	13 22	17 77	27 82	30 46	55 65	34 70	55 88	40 71	50 77	67 74	34 64	52 06	20 70	23 47
	2006																	
	Bahadur	31 89^{NS}	62 34^{NS}	119 64**	175 62**	286 24**	356 43**	440 59**	642 17**	771 04**	961 05**	993 57**	893 63**	653 63**	497 56**	424 84**	354 37**	269 95*
	Piolee	22 49^{NS}	54 65^{NS}	84 34**	143 78**	212 12**	252 17**	352 73**	520 34**	619 7**	671 94**	771 62**	592 17**	521 08**	389 64**	325 5**	290 14**	210 06*
	t values	1 98	1 62	7 42	6 69	15 58	21 91	18 47	25 61	31 81	40 58	44 20	26 94	27 86	22 68	20 88	13 50	12 59
Tiller number (hill^{-1})	2005																	
	Bahadur	4 25**	5 25*	7 25*	7 75*	9 50**	10 50**	11 25*	11 5*	11 75*	12 50**	11 75*	11 50**	10 25^{NS}	10 25^{NS}	10 00^{NS}	9 75^{NS}	9 25^{NS}
	Piolee	1 50**	3 75*	5 5*	6 25*	7 75**	8 75**	9 75*	10 25*	10 50*	10 75**	10 25*	10 00**	10 00^{NS}	10 00^{NS}	9 75^{NS}	9 50^{NS}	9 25^{NS}
	t values	4 26	3 67	2 71	3 67	3 97	3 97	3 67	2 84	2 84	3 97	3 67	4 50	0 34	0 34	0 34	0 39	0 00
	2006																	
	Bahadur	3 55**	5 53**	6 08**	7 60**	8 80**	9 90**	10 90*	11 18*	11 53*	11 30*	11 08*	10 80*	10 75*	9 98*	9 45^{NS}	9 28^{NS}	9 28^{NS}
	Piolee	1 08**	3 23**	5 40**	6 48**	7 50**	8 70**	10 15*	10 53*	10 88*	10 75*	10 50*	10 35*	10 2*	9 48*	9 35^{NS}	9 25^{NS}	9 15^{NS}
	t values	17 62	14 88	4 95	12 99	12 33	10 39	2 75	2 96	3 27	2 52	2 70	2 60	3 60	2 97	0 36	0 13	0 71

* = Significant at 0.05 level of significance; ** = Significant at 0.01 level of significance; ^{NS}= Non significant.

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

Table 4.1 represents the leaf area (cm^2 $hill^{-1}$) of Bahadur and Piolee. During 2005, leaf area was recorded 37.99cm^2 $hill^{-1}$ and 29.35cm^2 $hill^{-1}$ in Bahadur and Piolee respectively at 7 DAT, which started to increase gradually up to 1052.79cm^2 $hill^{-1}$ in Bahadur and 806.29cm^2 $hill^{-1}$ in Piolee at 77 DAT. Subsequently, decrease in leaf area was observed due to senescence and abscission of older leaves in both the varieties. During 2006, the recorded values were 31.39cm^2 $hill^{-1}$ and 22.49cm^2 $hill^{-1}$ in Bahadur and Piolee respectively at 7 DAT, which increased gradually up to 77 DAT (993.57cm^2 $hill^{-1}$ in Bahadur and 771.62cm^2 $hill^{-1}$ in Piolee). Bahadur recorded significantly higher leaf area compared to Piolee in both the years.

4.1.10. Leaf area index

Figure 4.6 represents the leaf area index of Bahadur and Piolee. In both the years, leaf area index increased gradually and obtained maximum values at 77 DAT. Decrease in leaf area index was observed later towards the maturation of the crop. Higher leaf area index was recorded in Bahadur compared to Piolee in both the years.

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

Tiller count of the varieties Bahadur and Piolee were done at weekly interval and the results are presented in Table 4.1. Variation in tiller number was observed in the varieties in both the years. Gradual increase in tiller number was recorded with the advancement of growth and development of the crop. In 2005, the highest tiller number of 12 and 10 $hill^{-1}$ was observed at 70 DAT in Bahadur and Piolee, respectively. After attaining the maximum tiller per hill, both the varieties recorded a gradual decrease in tiller number. Similar pattern of tiller development was recorded in the year 2006 with the highest tiller number of 11 and 10 $hill^{-1}$ at 63 DAT in Bahadur and Piolee, respectively.

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

Figure 4.7 represents the root length (cm hill^{-1}) of the varieties. In 2005, at initial stage (7 DAT), the recorded root length were 236.81 cm and 163.14 cm in variety Bahadur and Piolee respectively, which increased gradually and recorded 2057.81cm in Bahadur and 1753.24cm in Piolee at 84 DAT and 77 DAT, respectively. Gradual decrease in root length was observed till the harvest of the crop. In 2006, at 7 DAT, the root length were 177.16cm and 131.96cm in variety Bahadur and Piolee respectively, and obtained maximum 2147.92cm in Bahadur and 1665.08cm in Piolee at 84 DAT and 77 DAT, respectively. Higher root length was recorded in Bahadur compared to Piolee in both the years.

4.1.13. Root volume (ml hill^{-1})

Figure 4.8 represents the root volume (m hill^{-1}) of Bahadur and Piolee. At initial stage (7 DAT), the recorded root volume were 2.40ml and 1.52ml in variety Bahadur and Piolee respectively in 2005, which increased gradually up to 29.00ml in Bahadur and 25.63ml in Piolee at 84 DAT and 77 DAT, respectively. Subsequently, there was gradual decrease in root volume till the harvest of the crop. In 2006, at 7 DAT, the recorded root volumes were 3.35ml and 1.53ml in Bahadur and Piolee respectively, and maximum of 30.70ml in Bahadur and 24.40ml in Piolee were recorded at 84 DAT and 77 DAT, respectively. Bahadur recorded significantly higher root volume compared to Piolee in both the years.

4.1.14. Leaf blade dry weight (g hill^{-1})

Table 4.2 represents the dry weight (g hill^{-1}) of leaf blade of Bahadur and Piolee. In 2005, at initial stage (7 DAT), the leaf blade dry weight were 0.18 g and 0.13g in variety Bahadur and Piolee respectively, which increased gradually up to 11.05g in Bahadur and

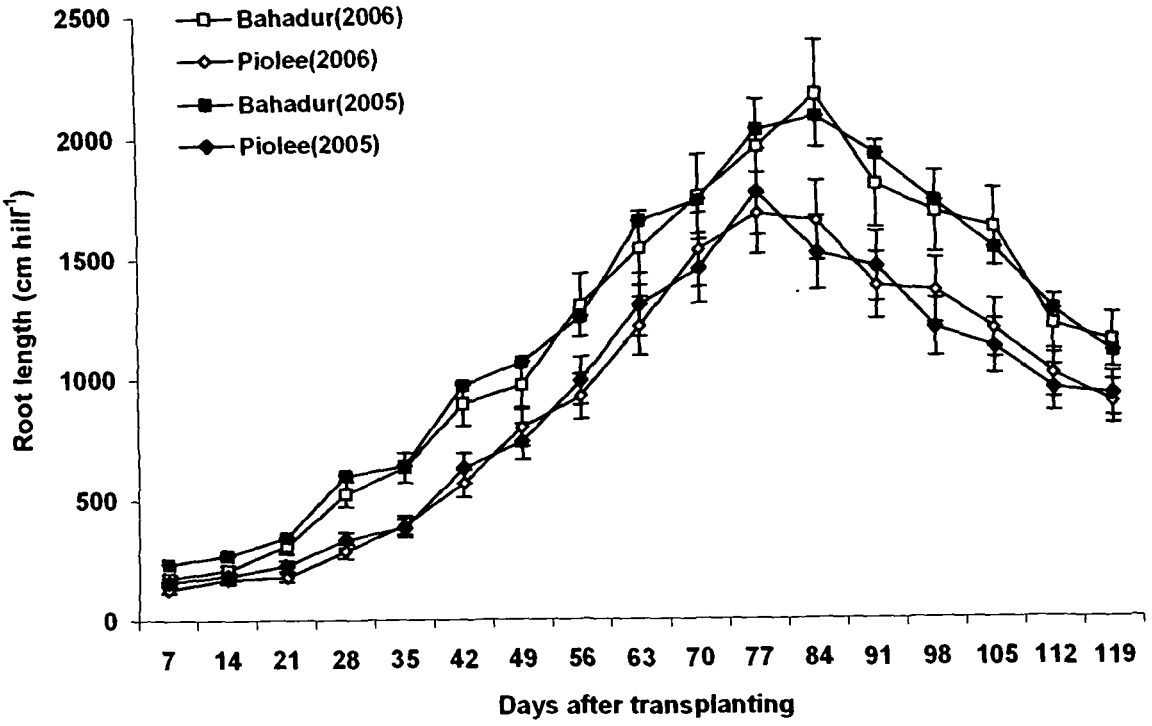


Fig. 4.7. Root length (cm hill^{-1}) of varieties Bahadur and Piolee. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

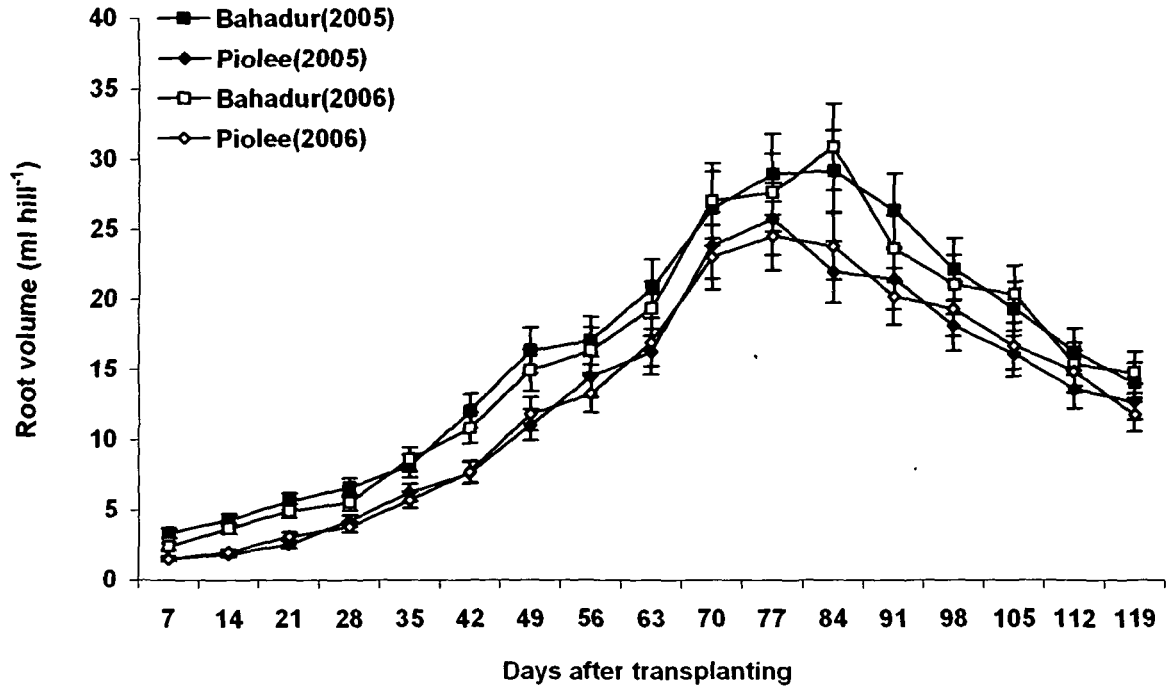


Fig. 4.8. Root volume (ml hill^{-1}) of varieties Bahadur and Piolee. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

9.69g in Piolee at 77 DAT. Subsequently, there was gradual decrease in leaf blade dry weight till the harvest of the crop. In 2006, at 7 DAT leaf blade dry weights were 0.16g and 0.12g in variety Bahadur and Piolee respectively, and obtained maximum of 10.74g in Bahadur and 9.14g in Piolee at 77 DAT, respectively. Bahadur recorded higher leaf blade dry weight compared to Piolee in both the years.

4.1.15. Leaf sheath dry weight (g hill^{-1})

Leaf sheath dry weight (g hill^{-1}) of Bahadur and Piolee was recorded at 7 days interval and values are presented in Table 4.2. In 2005, leaf sheath dry weight were 0.20g and 0.10g hill^{-1} at initial growth stage (7 DAT) in variety Bahadur and Piolee respectively, which increased gradually up to 11.94g hill^{-1} in Bahadur and 10.41g hill $^{-1}$ in Piolee at 77 DAT. There was gradual decrease in leaf sheath dry weight till the harvest of the crop. In 2006, the leaf sheath dry weights were 0.14g and 0.11g hill^{-1} in variety Bahadur and Piolee respectively at 7 DAT, and reached 11.46g hill^{-1} in Bahadur and 10.09g hill $^{-1}$ in Piolee at 77 DAT, respectively. Bahadur recorded higher leaf sheath dry weight compared to Piolee in both the years.

4.1.16. Culm dry weight (g hill^{-1})

Dry weight of culm (g hill^{-1}) of Bahadur and Piolee was recorded at 7 days interval and data are presented in Table 4.2. In 2005, at initial stage (7 DAT), 0.37g and 0.31g hill^{-1} dry weights were recorded in variety Bahadur and Piolee respectively, which increased gradually up to 20.17g hill^{-1} in Bahadur and 18.44g hill $^{-1}$ in Piolee at harvest. In 2006, at 7 DAT, the dry weights were 0 29g and 0.22g hill^{-1} in variety Bahadur and Piolee respectively, and obtained maximum at harvest 19.60g hill^{-1} in Bahadur and 17.60g hill $^{-1}$ in Piolee, respectively. Bahadur recorded higher culm dry weight compared to Piolee in both the years.

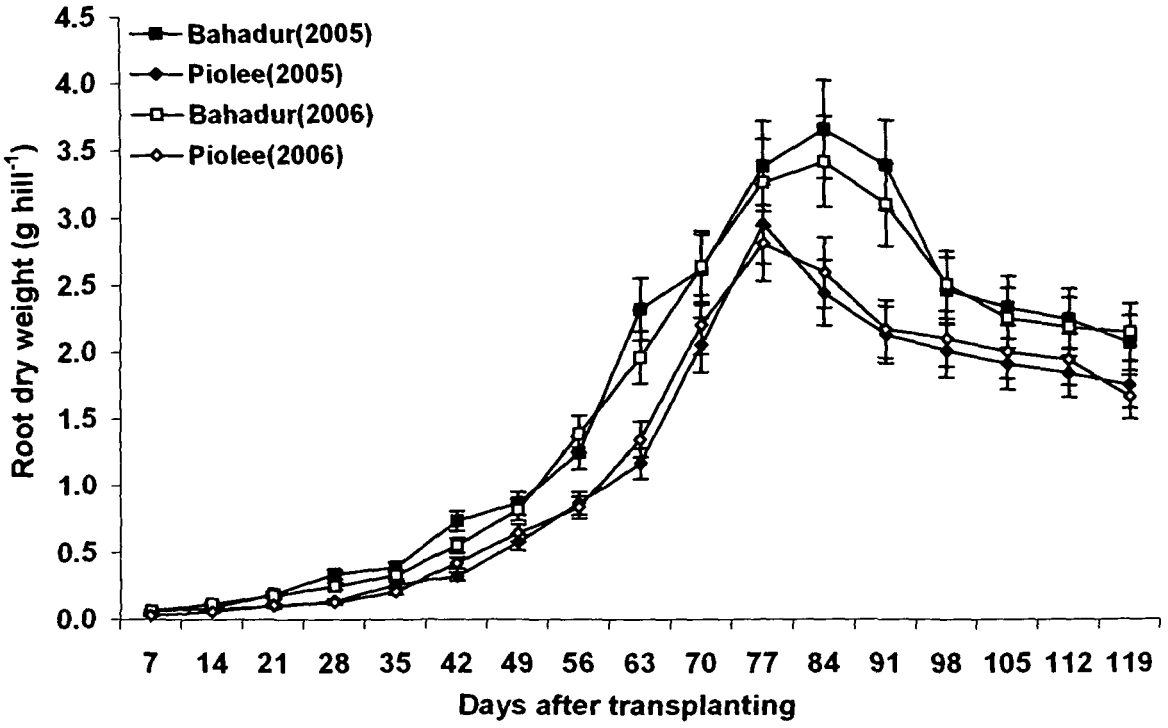


Fig. 4.9. Root dry weight (g hill^{-1}) of varieties Bahadur and Piolee. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

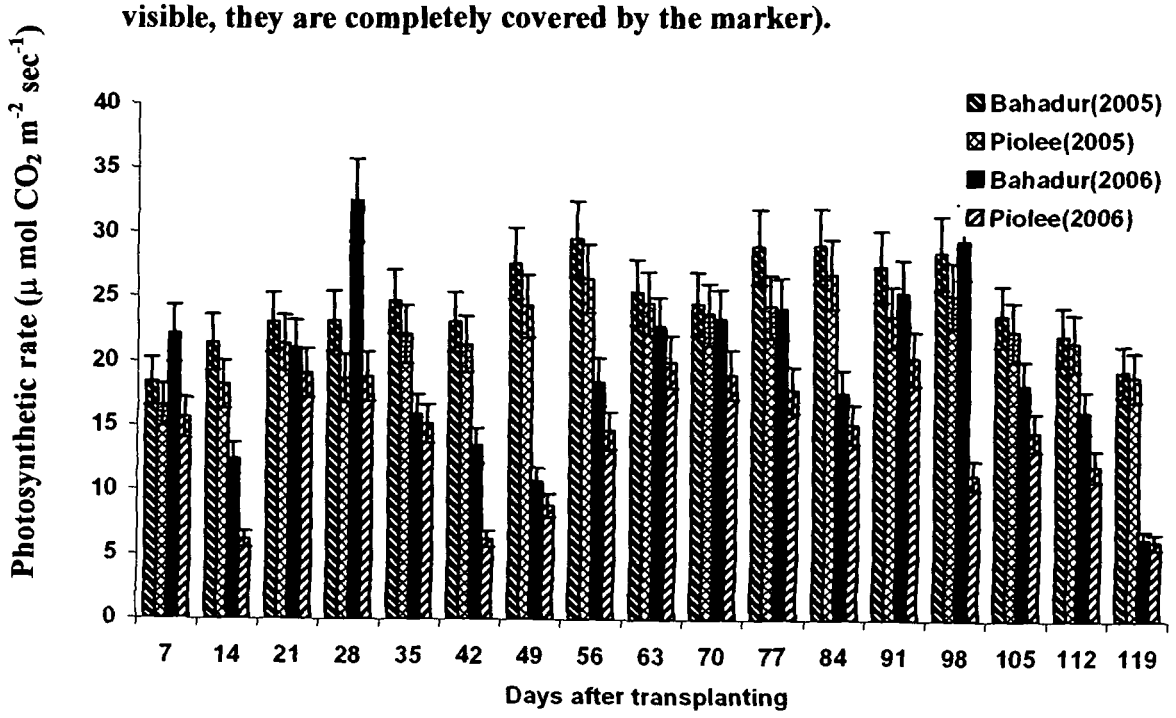


Fig. 4.10. Photosynthetic rate (μmol CO_2 m^{-2} sec^{-1}) of varieties Bahadur and Piolee. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

Table 4.2. Comparison of dry weights (g hill^{-1}) of different plant parts (leaf blade, leaf-sheath, culm and shoot) between varieties Bahadur and Piolee grown in monsoon / *Sali* ecosystem.

Dry weight (g hill^{-1})		Days after transplanting																
		7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119
	2005																	
	Bahadur	0 18^{NS}	0 21^{NS}	0 53*	1 65**	2 27**	2 84**	4 02**	7 29**	8 87**	10 77**	11 05**	9 84**	9 11**	7 87**	6 63**	5 93**	5 58**
Leaf blade	Piolee	0 13^{NS}	0 18^{NS}	0 42*	0 74**	1 67**	2 13**	2 83**	4 14**	6 86**	8 28**	9 68**	9 10**	6 89**	6 46**	5 34**	5 07**	4 57**
	t values	1 25	0 66	3 02	26 58	17 45	20 69	34 83	92 56	58 98	73 12	40 13	21 57	65 16	41 31	37 77	25 11	29 53
	2006																	
	Bahadur	0 16^{NS}	0 19^{NS}	0 51**	1 03**	2 01**	2 62**	3 39**	6 41**	8 44**	10 26**	10 74**	10 54**	8 49**	7 48**	6 41**	6 16**	5 24**
	Piolee	0 12^{NS}	0 16^{NS}	0 4**	0 72**	1 48**	1 78**	2 40**	4 53**	6 00**	8 60**	9 14**	8 36**	7 32**	5 88**	5 73**	5 34**	5 07**
	t values	1 40	1 03	4 01	11 46	19 67	31 22	36 82	70 00	90 88	61 80	59 56	81 18	43 53	59 56	25 26	30 48	6 25
Leaf	2005																	
sheath	Bahadur	0 20^{NS}	0 29^{NS}	0 77**	0 91**	2 27**	3 45**	4 06**	6 37**	8 86**	11 53**	11 94**	11 93**	9 77**	8 16**	7 61**	6 89**	6 70**
	Piolee	0 10^{NS}	0 21^{NS}	0 43**	0 72**	1 52**	2 56**	3 07**	4 65**	6 88**	8 25**	10 41**	9 29**	8 72**	7 03**	6 61**	5 81**	5 38**
	t values	2 37	1 89	8 22	4 57	18 20	21 61	24 05	38 54	55 00	74 17	37 20	50 17	26 22	27 46	24 29	26 24	32 09
	2006																	
	Bahadur	0 14^{NS}	0 16^{NS}	0 47**	0 88**	1 73**	3 26**	3 78**	6 81**	7 97**	10 76**	11 46**	11 30**	10 41**	8 54**	8 08**	6 66**	6 09**
	Piolee	0 11^{NS}	0 16^{NS}	0 38**	0 69**	1 14**	2 16**	2 64**	5 09**	5 94**	8 84**	10 09**	9 71**	8 90**	7 44**	6 31**	6 11**	5 49**
	t values	0 99	0 00	4 15	7 62	9 59	44 10	22 27	70 08	82 76	29 97	55 75	44 77	60 54	50 59	75 60	22 05	24 25
Culm	2005																	
	Bahadur	0 37^{NS}	0 77**	0 91**	1 16**	1 90**	3 57**	7 14**	8 83**	12 16**	12 80**	14 79**	15 77**	16 66**	18 6**	19 68**	19 74**	20 17**
	Piolee	0 31^{NS}	0 60**	0 73**	0 94**	1 57**	2 57**	4 00**	5 22**	8 66**	11 00**	11 53**	13 54**	15 20**	16 11**	17 52**	18 11**	18 44**
	t values	1 29	3 76	3 98	4 88	7 35	22 38	70 40	92 01	64 35	40 33	19 78	49 98	32 70	55 82	48 41	36 52	13 19
	2006																	
	Bahadur	0 29^{NS}	0 69**	0 83**	1 40**	2 26**	3 26**	5 73**	8 47**	10 40**	12 29**	13 75**	15 86**	17 19**	18 19**	19 19**	19 52**	19 60**
	Piolee	0 22^{NS}	0 51**	0 64**	0 85**	1 48**	2 19**	3 00**	5 90**	7 89**	10 38**	12 38**	13 75**	14 64**	15 45**	17 01**	17 34**	17 60**
	t values	1 83	4 71	4 97	14 39	20 41	27 99	71 42	67 23	65 67	49 97	35 84	55 20	66 71	71 68	57 03	57 03	52 32
Shoot	2005																	
	Bahadur	0 74**	1 26**	2 20**	3 71**	6 43**	9 85**	15 21**	22 49**	29 88**	35 09**	37 77**	37 54**	35 53**	34 62**	33 91**	32 55**	32 44**
	Piolee	0 54**	0 99**	1 58**	2 40**	4 76**	7 26**	9 90**	14 01**	22 40**	27 53**	31 62**	31 94**	30 82**	29 6**	29 47**	28 99**	28 39**
	t values	6 51	8 82	20 37	43 12	54 99	85 33	175 04	135 14	113 92	331 60	30 79	105 00	127 54	165 47	146 34	117 32	24 77
	2006																	
	Bahadur	0 58**	1 03**	1 81**	3 30**	5 99**	9 13**	12 90**	21 68**	26 8**	33 30**	35 94**	37 70**	36 08**	34 21**	33 68**	32 33**	30 92**
	Piolee	0 45**	0 82**	1 41**	2 25**	4 10**	6 13**	8 04**	15 52**	19 83**	27 82**	31 61**	31 82**	30 85**	28 77**	29 04**	28 78**	28 16**
	t values	4 60	8 12	15 63	41 00	25 42	110 14	77 52	220 88	249 92	73 65	155 26	141 74	204 60	201 65	183 37	138 85	98 97

*=Significant at 0.05 level of significance; ** = Significant at 0.01 level of significance; ^{NS}= Non significant.

4.1.17. Shoot dry weight (g hill^{-1})

Shoot dry weight (g hill^{-1}) of Bahadur and Piolee was recorded at 7 days interval and data are presented in Table 4.2. In 2005, at 7 DAT, the shoot dry weights were 0.74g and 0.54g hill^{-1} in variety Bahadur and Piolee respectively, which increased gradually up to 37.77g hill^{-1} in Bahadur at 77 DAT, and 31.94g hill $^{-1}$ in Piolee at 84 DAT. Gradual decrease in shoot dry weight was recorded till the harvest of the crop. In 2006, at 7 DAT, dry weights were 0.58g and 0.45g hill^{-1} and at 84 DAT it was 37.70g hill $^{-1}$ in Bahadur and 31.82g hill^{-1} in Piolee respectively. Bahadur recorded higher shoot dry weight compared to Piolee in both the years.

4.1.18. Root dry weight (g hill^{-1})

Figure 4.9 represents the root dry weight (g hill^{-1}) of Bahadur and Piolee. In 2005, at 7 DAT, the root dry weights were 0.06g and 0.07g hill^{-1} in Bahadur and Piolee respectively, and were 3.63g hill^{-1} in Bahadur and 2.93g hill $^{-1}$ in Piolee at 84 DAT and 77 DAT, respectively. Subsequently, there was gradual decrease in root dry weight till the harvest of the crop. In 2006, at 7 DAT, the dry weights were 0.07g and 0.03g hill^{-1} in variety Bahadur and Piolee respectively, and reached maximum 3.39g hill^{-1} in Bahadur and 2.79g hill $^{-1}$ in Piolee at 84 DAT and 77 DAT, respectively. Bahadur recorded higher root dry weight compared to Piolee in both the years.

4.1.19. Leaf photosynthetic rate (μ mol CO_2 m^{-2} sec^{-1})

Leaf photosynthetic rates (μ mol CO_2 m^{-2} sec^{-1}) of the two varieties were recorded at weekly interval and data are presented in Figure 4.10. Significant cultivar differences in photosynthetic rate were observed. In both the years, higher rate of photosynthesis was recorded in Bahadur compared to Piolee.

Table 4.3. Comparisons of yield and yield attributing parameters of varieties Bahadur and Piolee grown in monsoon / *Sali* ecosystem.

Parameters	2005			2006		
	Bahadur	Piolee	t value	Bahadur	Piolee	t value
1000 grain weight (g)	19.08*	19.23*	3.67	19.08*	19.28*	2.56
Filled grain (%)	75.25*	76.25*	2.45	75.50*	77.25*	2.71
Panicle plant^{-1}	10.25*	11.25*	2.45	9.75*	10.75*	2.45
Spikelet panicle^{-1}	85.00*	87.00*	2.45	85.75*	88.00*	3.10
Panicle (m $^{-2}$)	256.25*	281.25*	2.45	253.00*	266.25*	2.61
Panicle length (cm)	21.23^{NS}	20.03^{NS}	2.35	21.55**	19.08**	14.63
Panicle dry weight (g hill^{-1})	18.47*	21.28*	2.51	17.48*	20.43*	2.64
Yield (t ha^{-1})	3.14**	3.26**	5.98	3.11**	3.33**	5.99

* = Significant at 0.05 level of significance; ** = Significant at 0.01 level of significance; ^{NS} = Non significant.

4.1.20. Dry weight of developing panicle

After panicle initiation, dry weights (g) of developing panicles per hill of Bahadur and Piolee were recorded at 7 at interval till harvest and are presented in Figure 4.11. In 2005, at 77 DAT, the panicle dry weights were 0.23g and 0.34g $hill^{-1}$ in variety Bahadur and Piolee respectively, which increased to 18.47g $hill^{-1}$ in Bahadur and 21.28g $hill^{-1}$ in Piolee, respectively at harvest. In 2006, at 77 DAT, the panicle dry weights were 0.15g and 0.28g $hill^{-1}$ in variety Bahadur and Piolee respectively, and 17.48g $hill^{-1}$ in Bahadur and 20.43g $hill^{-1}$ in Piolee, at harvest. Piolee recorded higher dry weight of developing panicle compared to Bahadur in both the years.

4.1.21. Yield

Data recorded on yield and yield attributing parameters of the varieties are presented in Table 4.3. Variety Piolee recorded higher grain yield (2005: 3.26t ha^{-1}: 2006: 3.33t ha^{-1}) than Bahadur (2005: 3.14t ha^{-1}: 2006: 3.11t ha^{-1}) in both the years. Thousand grain weight (2005: 19.08g in Bahadur, 19.23g in Piolee; 2006: 19.08g in Bahadur, 19.28g in Piolee), filled grain (2005: 75.25% in Bahadur, 76.25% in Piolee; 2006: 75.50% in Bahadur, 77.25% in Piolee) , number of panicle per hill (2005: 10.25 $hill^{-1}$ in Bahadur, 11.25 $hill^{-1}$ in Piolee; 2006: 9.75 $hill^{-1}$ in Bahadur, 10.75 $hill^{-1}$ in Piolee) , spikelet number per panicle (2005: 85.00 $panicle^{-1}$ in Bahadur, 87.00 $panicle^{-1}$ in Piolee; 2006: 85.75 $panicle^{-1}$ in Bahadur, 88.00 $panicle^{-1}$ in Piolee), number of panicle per unit area (2005: 256.25m^{-2} in Bahadur, 281.25m^{-2} in Piolee; 2006. 253.00m^{-2} in Bahadur, 266.25m^{-2} in Piolee) and panicle dry weight (2005: 21.23g $hill^{-1}$ in Bahadur, 20.03g $hill^{-1}$ in Piolee; 2006: 21.55g $hill^{-1}$ in Bahadur, 19.08g $hill^{-1}$ in Piolee) were also higher in Piolee compared to Bahadur. Variety Bahadur recorded higher panicle length (2005: 21.23cm in Bahadur, 20.03cm in Piolee; 2006: 21.55cm in Bahadur, 19.08cm in Piolee).

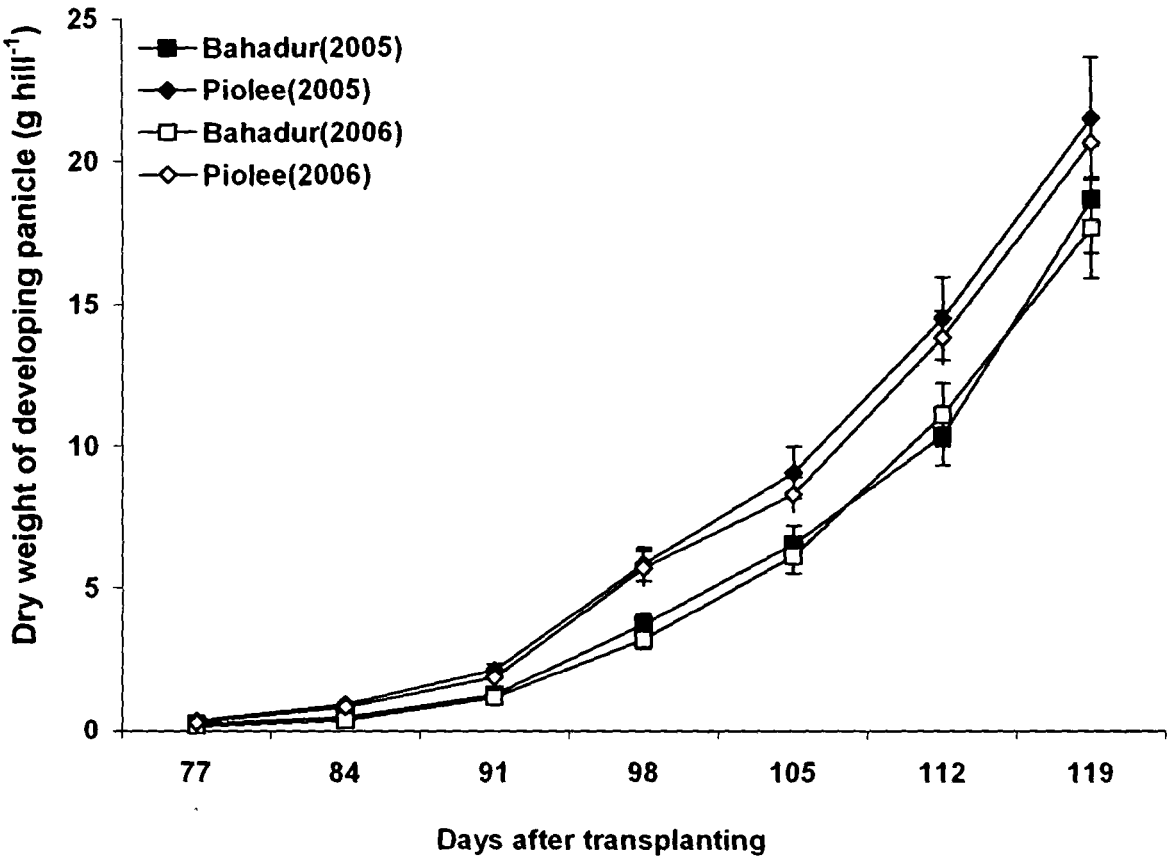


Fig. 4.11. Dry weight (g hill^{-1}) of developing panicle of varieties Bahadur and Piolee. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

Table 4.4. Correlation of plant and soil parameters with methane emission from varieties Bahadur and Piolee grown in monsoon / *Sali* ecosystem.

	Correlation with methane emission			
Parameters	**2005**		**2006**	
	Bahadur	**Piolee**	**Bahadur**	**Piolee**
Plant height	NS	NS	NS	NS
Leaf No	0.72**	0.75**	0.67**	0.71**
Leaf area	0.78**	0.83**	0.82**	0.81**
LAI	0.78**	0.83**	0.82**	0.81**
Tiller No	0.79**	0.67**	0.70**	0.59*
Root length	0.58*	0.56*	0.67**	0.62**
Root volume	0.62**	0.52*	0.68**	0.63**
Root dry weight	NS	NS	0.50*	NS
Leaf blade dry weight	0.52*	0.49*	0.67**	0.56*
Leaf sheath dry weight	NS	NS	0.63**	0.55*
Culm dry weight	NS	NS	NS	NS
Shoot dry weight	NS	NS	NS	NS
Photosynthesis	NS	NS	0.82**	0.84**
Organic carbon	0.83**	0.74**	0.79**	0.71**
Soil pH	0.71**	0.70**	0.67**	0.63**
Soil temperature	NS	NS	0.54**	0.56**

* = Correlation is significant at the 0.05 level of significance; ** = Correlation is significant at the 0.01 level of significance; NS = Non significant

4.2. Association of plant growth parameters with methane emission from irrigated / *Boro* rice

4.2.1. Meteorological parameters

Figure 3.3 and 3.4 represent the meteorological parameters i.e. rainfall (mm) and air temperature in ^{0}C (both maximum and minimum) at weekly interval of the crop-growing season. Lower temperatures were recorded during the initial stage of crop growth (January-February) in both the years. Gradual increase in temperature was observed towards the end of the crop growing season (May- June).

4.2.2. Methane flux (mg CH_4 m^{-2} hr^{-1})

Measurement of methane flux from rice cultivars (2006 and 2007) Agni and Ranjit grown in irrigated condition indicated cultivar differences in flux rate (Fig. 4.12). In both the years higher methane flux (mg CH_4 m^{-2} hr^{-1}) was recorded from the cultivar Agni. Seasonal integrated methane flux (E_{sif}) was also higher in cultivar Agni (E_{sif} in 2006 was 7.15g m^{-2} and in 2007, it was 7.42g m^{-2}) compared to Ranjit (E_{sif} in 2006 was 5.42g m^{-2} and in 2007, it was 5.76g m^{-2}). Despite of these differences, seasonal pattern of CH_4 emission from both the cultivars was similar in nature in both the years. Methane flux was initially very low and then increased with age of the rice plants. Two distinct methane emission peaks were detected. The first was during active vegetative growth (42 DAT in Agni; and at 49 DAT in Ranjit). The second was at panicle initiation (63 DAT in

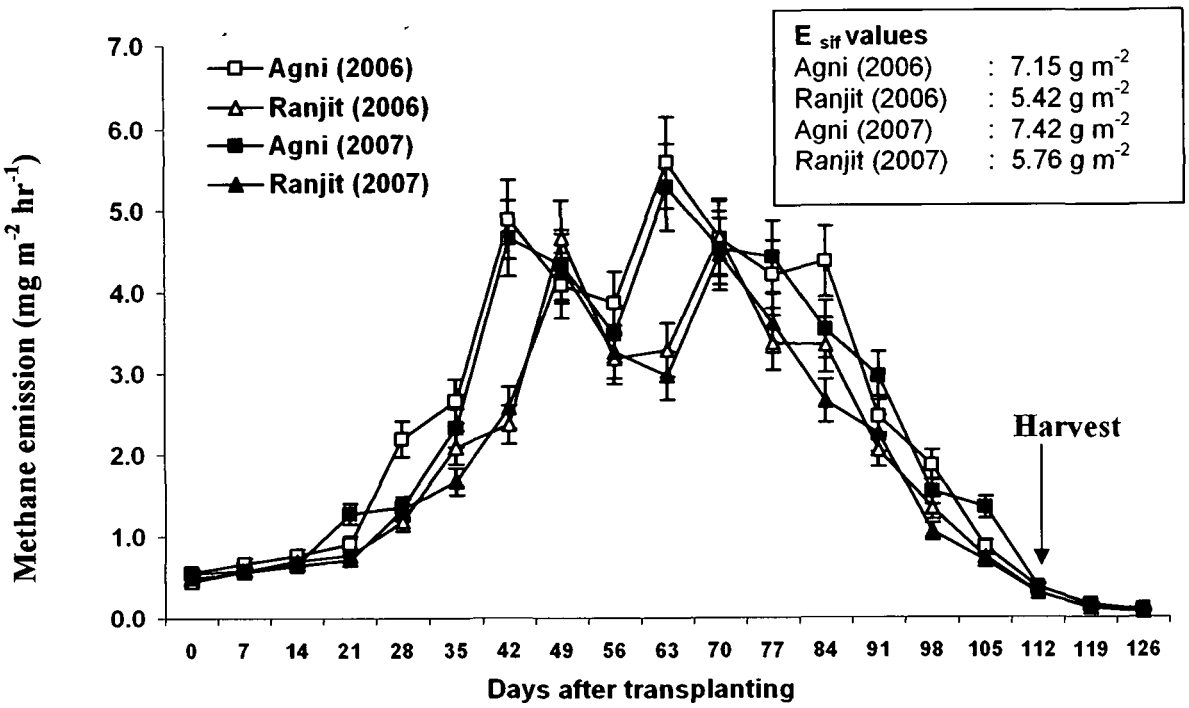


Fig. 4.12. Methane emission (mg m^{-2} hr^{-1}) from cultivars Agni and Ranjit at different growth stages. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

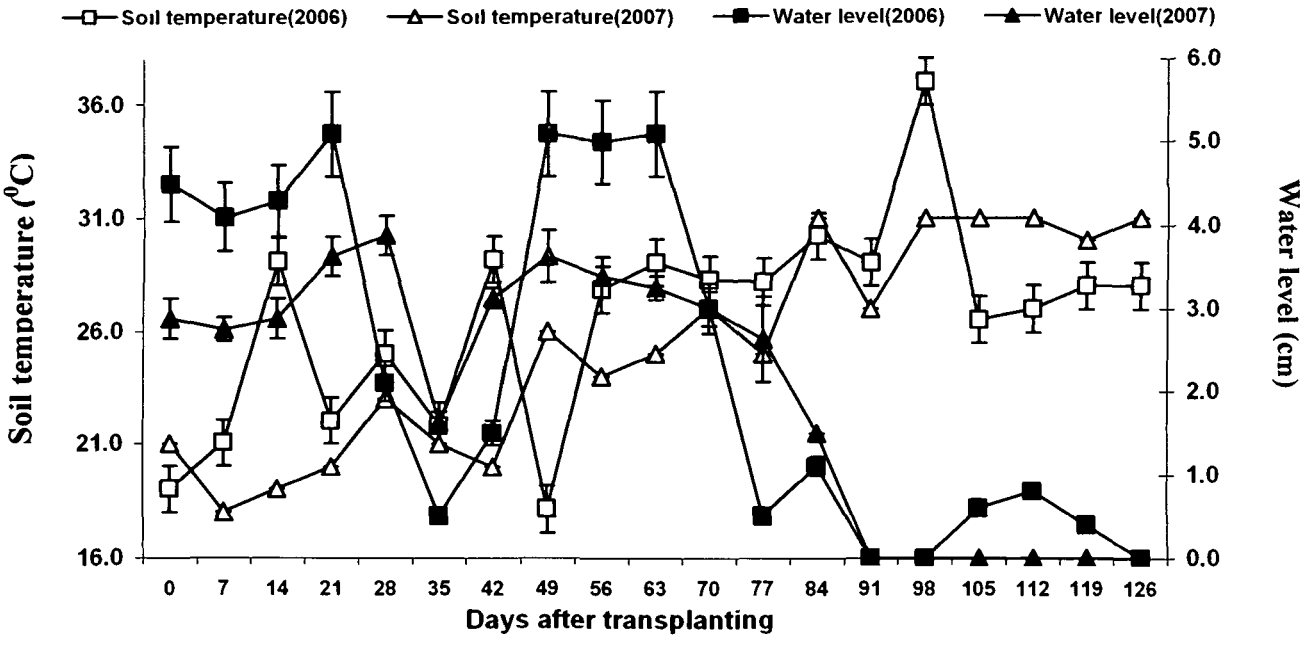


Fig. 4.13. Water level (cm) and soil temperature (^{0}C) of the experimental field planted with cultivars Agni and Ranjit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

Table 4.5. Comparison of plant height, leaf number, leaf area and tiller number (hill^{-1}) between cultivars Agni and Ranjit grown in irrigated / *Boro* ecosystem.

	Days after transplanting															
	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112
Plant height (cm)																
2006																
Agni	18 13**	26 25**	39 13**	62 75**	66 00**	76 38**	92 38**	102 63**	126 88**	135 25**	137 63**	137 81**	138 02**	138 19**	138 38**	139 08**
Ranjit	13 00**	20 25**	29 13**	43 50**	58 88**	67 75**	70 00**	84 88**	109 00**	116 50**	116 67**	116 87**	117 02**	117 11**	117 25**	117 32**
t values	5 22	5 20	8 20	13 34	6 25	4 35	14 76	10 37	7 69	7 745	8 763	8 876	8 99	8 96	8 96	9 70
2007																
Agni	18 73**	19 98**	24 73**	30 33**	40 30**	46 44**	79 26**	99 98**	108 63**	123 85**	127 34**	129 20**	129 98**	131 00**	131 95**	133 10**
Ranjit	16 03**	17 93**	21 80**	26 88**	35 21**	42 18**	58 70**	78 79**	97 99**	112 53**	113 99**	115 69**	115 83**	116 40**	116 64**	117 31**
t values	3 96	6 81	6 53	9 72	3 57	4 86	66 05	75 13	19 10	27 72	38 05	15 19	20 84	43 80	49 77	72 919
Leaf no																
2006																
Agni	10 25^{NS}	14 75*	21 75**	44 50**	51 50**	64 00*	90 5*	105 50*	123 50*	130 75**	126 25**	123 75*	120 25**	117 75*	113 75*	109 75**
Ranjit	9 00^{NS}	11 00*	16 25**	24 75**	32 00**	57 50*	83 00*	99 25*	113 50*	124 00**	120 25**	117 75*	114 50**	112 00*	110 00*	100 75**
t values	0 75	3 15	3 74	10 20	6 50	2 73	3 21	2 84	2 97	4 246	5 308	2 51	4 09	2 70	2 60	4 665
2007																
Agni	8 80**	11 48**	13 75**	16 93**	24 85**	32 10**	74 65**	82 98**	106 95**	125 00**	112 33**	91 45**	87 63**	85 93**	84 03**	82 05**
Ranjit	6 63**	9 85**	11 65**	14 00**	18 33**	27 28**	58 18**	73 45**	97 68**	112 40**	99 95**	80 28**	76 68**	75 10**	73 40**	71 80**
t values	4 43	6 01	6 12	8 19	8 76	10 12	11 09	32 83	7 95	31 07	13 33	14 27	16 48	17 80	21 96	18 54
Leaf area (cm^2)																
2006																
Agni	37 62^{NS}	59 59**	123 45**	141 16**	199 48**	300 77**	509 80**	792 86**	1022 95**	1688 80**	1590 35**	1513 21**	1361 41*	1267 94**	987 80**	783 04**
Ranjit	34 00^{NS}	46 62**	85 87**	94 71**	157 20**	252 45**	418 50**	629 86**	884 92**	1589 95**	1498 40**	1354 84**	1293 44*	1184 15**	879 48**	606 35**
t values	2 31	6 43	10 77	12 76	6 98	6 45	12 34	15 10	4 94	7 57	6 53	3 85	2 58	2 95	23 66	42 996
2007																
Agni	38 61**	45 16**	58 84**	102 26**	197 56**	255 01**	490 24**	750 94**	927 24**	1518 76**	1422 08**	1313 30**	1216 86**	1148 70**	1032 21**	807 29**
Ranjit	32 61**	37 09**	46 12**	83 67**	166 86**	213 17**	395 24**	607 51**	823 54**	1411 37**	1300 17**	1195 98**	1046 98**	974 15**	902 97**	707 98**
t values	4 19	3 56	6 42	5 09	8 65	4 76	19 27	18 15	10 33	9 54	7 50	8 35	6 83	4 43	5 35	9 96
Tiller no																
2006																
Agni	0 00^{NS}	0 00^{NS}	4 50**	9 00**	11 50**	17 75**	25 00**	24 75**	24 00**	23 50**	22 25**	21 25**	20 50**	19 75**	18 75**	16 75**
Ranjit	0 00^{NS}	0 00^{NS}	2 50**	6 50**	8 25**	15 5**	20 50**	20 25**	20 25**	20 25**	19 00**	16 75**	16 00**	15 75**	14 25**	12 50**
t values	-	-	4 24	4 33	5 04	5 10	5 10	4 93	4 33	4 07	4 47	5 76	6 04	6 41	4 93	4 58
2007																
Agni	0 00	1 80*	3 33^{NS}	7 85**	9 18**	11 28**	15 83**	16 55**	17 10**	16 68**	15 48**	15 15**	14 45**	14 25**	14 13**	14 03**
Ranjit	0 00	1 48*	3 58^{NS}	6 23**	7 98**	9 30**	12 30**	13 45**	15 10**	15 05**	13 40**	13 10**	12 55**	12 25**	12 10**	12 00**
t values	-	3 30	1 01	4 31	7 43	12 42	9 25	5 07	5 39	3 45	4 76	5 50	8 23	8 32	8 89	8 53

* = Significant at 0.05 level of significance; ** = Significant at 0.01 level of significance; ^{NS} = Non significant.

Table 4.6. Comparison of dry weights of leaf blade, leaf sheath, culm and shoot (g hill^{-1}) between cultivars Agni and Ranjit grown in irrigated / *Boro* ecosystem.

		Days after transplanting															
		7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112
Leaf	2006																
blade	Agni	0 19^{NS}	0 25*	0 49**	0 70**	1 19**	1 95*	2 16*	6 02**	8 17**	10 08*	8 94*	8 40*	7 86**	6 74*	5 62**	5 45**
dry	Ranjit	0 17^{NS}	0 21*	0 26**	0 57**	1 06**	1 69*	2 07*	5 65**	7 83**	9 85*	8 64*	8 14*	7 36**	6 54*	5 17**	5 04**
weight	t values	1 57	2 48	10 65	4 99	4 45	3 35	2 74	4 69	5 35	2 96	3 03	2 78	4 58	2 71	5 02	4 77
(g hill^{-1})	2007																
	Agni	0 19**	0 21^{NS}	0 30**	0 41**	0 99**	1 73**	2 40**	5 26**	7 42**	9 11**	8 68**	7 88**	7 30**	5 40*	4 96**	4 84**
	Ranjit	0 16**	0 19^{NS}	0 23**	0 34**	0 83**	1 28**	1 90**	4 25**	4 94**	7 20**	7 15**	6 94**	5 76**	4 87*	4 33**	4 25**
	t values	3 84	2 21	5 47	5 16	8 56	8 54	21 21	18 10	33 70	30 64	15 52	11 22	11 08	2 77	5 36	9 93
Leaf	2006																
sheath	Agni	0 06*	0 08**	0 10**	0 17**	0 29**	0 40**	0 48**	1 29**	2 41**	3 96**	3 97**	4 08**	3 98**	3 72**	3 28**	3 15**
dry	Ranjit	0 04*	0 05**	0 07**	0 11**	0 15**	0 19**	0 40**	1 02**	2 01**	3 08**	3 08**	3 09**	3 05**	2 98**	2 39**	2 24**
weight	t values	2 69	3 78	6 45	6 57	8 78	16 60	5 06	8 72	8 65	20 44	23 37	34 50	22 80	5 18	9 43	11 01
(g hill^{-1})	2007																
	Agni	0 08**	0 09*	0 11NS	0 11*	0 24*	0 40**	0 51**	1 58**	2 90**	4 01**	4 08**	4 41**	4 40**	4 21**	4 12**	4 07**
	Ranjit	0 06**	0 07*	0 10NS	0 12*	0 23*	0 31**	0 44**	0 89**	1 48**	2 81**	3 15**	3 40**	3 37**	3 31**	3 29**	3 23**
	t values	3 97	2 84	2 12	2 45	2 84	7 23	14 85	46 07	53 93	47 06	20 14	21 88	11 27	6 39	8 44	17 37
Culm	2006																
dry	Agni	0 15^{NS}	0 26**	0 39**	0 53**	1 27*	1 72**	2 30**	5 77**	7 97**	8 41**	8 76**	9 37**	9 90**	10 12**	11 42**	11 21**
weight	Ranjit	0 09^{NS}	0 18**	0 28**	0 40**	0 90*	1 10**	1 75**	4 65**	6 06**	6 97**	7 54**	7 95**	8 13**	8 43**	9 14**	9 07**
(g hill^{-1})	t values	1 63	2 83	7 14	5 00	2 71	4 31	3 26	6 49	23 43	6 00	5 10	6 99	22 02	16 64	9 45	10 33
	2007																
	Agni	0 13^{NS}	0 18**	0 24**	0 29**	0 73**	1 25**	3 09**	6 00**	6 52**	8 05**	8 92**	9 04**	9 75**	10 48**	10 56**	10 65**
	Ranjit	0 11^{NS}	0 16**	0 21**	0 24**	0 53**	0 63**	1 17**	4 73**	5 59**	6 75**	6 84**	8 10**	8 11**	8 96**	9 33**	9 97**
	t values	2 41	7 79	9 53	9 64	7 26	36 83	156 77	72 65	29 83	45 64	90 80	15 55	32 16	58 15	49 12	40 86
Shoot	2006																
dry	Agni	0 40^{NS}	0 59**	0 99**	1 39**	2 76**	4 07**	4 93*	13 07**	18 55**	22 44**	21 67**	21 84**	21 74**	20 58**	20 32**	19 80**
weight	Ranjit	0 31^{NS}	0 45**	0 60**	1 07**	2 11**	2 98**	4 22*	11 32**	15 90**	19 90**	19 26**	19 18**	18 55**	17 95**	16 70**	16 34**
(g hill^{-1})	t values	1 87	3 72	9 20	6 15	3 94	5 20	3 48	6 43	17 76	7 53	6 67	9 18	16 24	11 56	11 66	14 62
	2007																
	Agni	0 40**	0 48**	0 64**	0 81**	1 95**	3 39**	6 00**	12 83**	16 83**	21 17**	21 67**	21 34**	21 45**	20 09**	19 63**	19 56**
	Ranjit	0 33**	0 42**	0 54**	0 70**	1 59**	2 22**	3 50**	9 87**	12 01**	16 76**	17 14**	18 44**	17 24**	17 15**	16 96**	17 44**
	t values	7 82	3 79	5 72	5 47	10 94	17 56	83 95	37 53	49 09	46 23	28 88	15 52	16 95	9 28	13 13	19 41

* = Significant at 0.05 level of significance; ** = Significant at 0.01 level of significance; ^{NS} = Non significant.

Agni; 70 DAT in Ranjit). There was decline in emission after panicle initiation in both the cultivars and was very low at harvest. Methane emission was negligible after harvest.

4.2.3. Water level (cm)

Weekly field water level is presented in Figure 4.13. Rainfall and field irrigation kept the experimental plots submerged during most of the growth period (up to 91 DAT in both the years).

4.2.4. Soil organic carbon (%)

Soil organic carbon content (%) was initially low (0.95% in 2006 and 0.96% in 2007 for both the cultivars at 0 DAT), reached maximum at active tillering (2006: 1.32% at 42 DAT for Agni and 1.31% at 49 DAT for Ranjit; 2007: 1.39% at 42 DAT for Agni and 1.34% at 49 DAT for Ranjit) and panicle initiation stage (2006: 1.42% at 63 DAT for Agni and 1.35% at 70 DAT for Ranjit; 2007: 1.42% at 63 DAT for Agni and 1.36% at 70 DAT for Ranjit) of the crop (Fig. 4.14). This trend was observed in both the plots planted with the cultivars irrespective of the seasons. Higher soil organic carbon content was recorded in plots of Agni compared to Ranjit. A highly significant positive correlation was found between methane emission and soil organic carbon content (Table 4.8).

4.2.5. Soil temperature (^{0}C)

Figure 4.13 represents the soil temperatures (^{0}C) at weekly interval of the experimental fields. Values presented are the recorded soil temperatures from 0 DAT to two weeks after harvest. Lower temperature was observed (2006: 19.00°C at

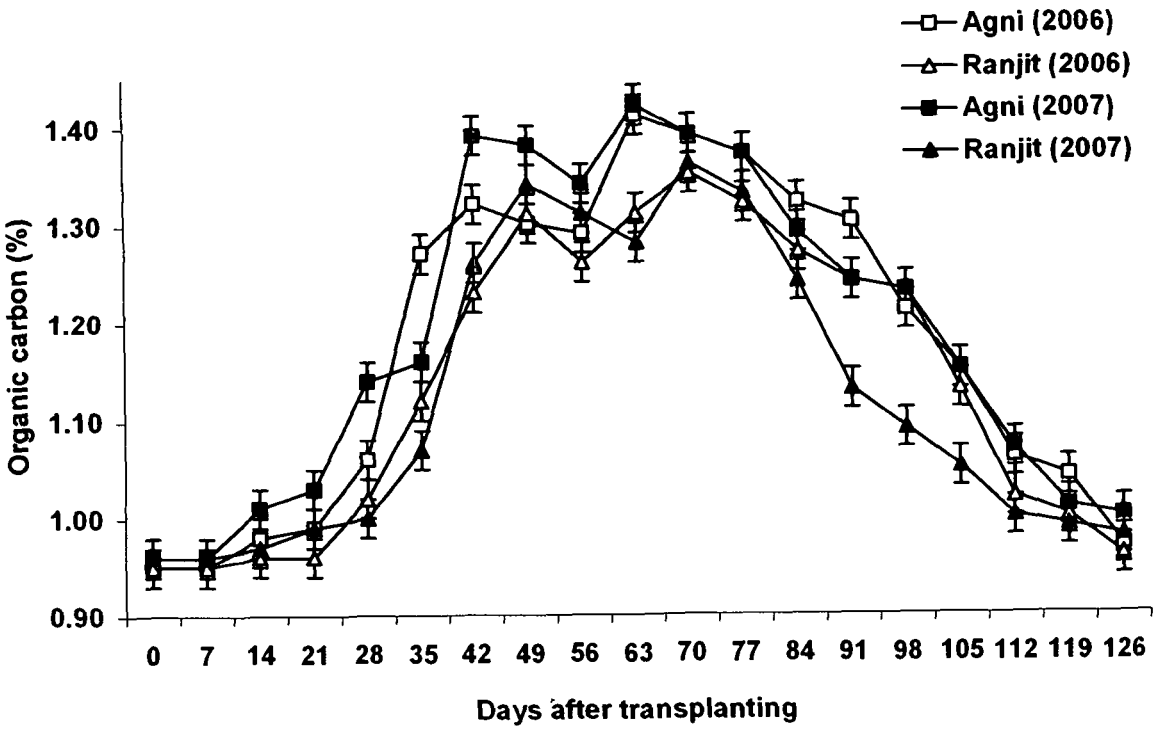


Fig. 4.14. Organic carbon (%) of the experimental field (cultivars Agni and Ranjit). Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

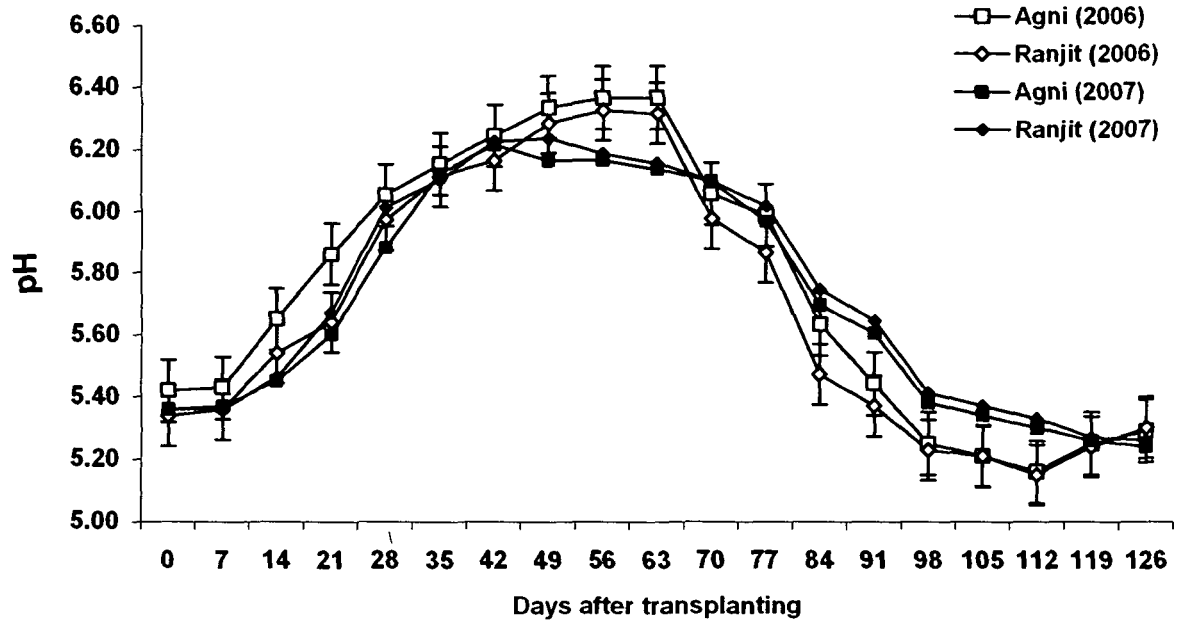


Fig. 4.15. Soil pH of the experimental field (cultivars Agni and Ranjit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

0 DAT; 2007: 18.00°C at 7DAT) during the initial stage of crop growth. During the crop maturation stage, higher soil temperatures were recorded (2006: 37.00°C at 98 DAT; 2007: 31.00°C at 84, 98, and 105 DAT).

4.2.6. Soil pH

Figure 4.15 represents the soil pH measured at weekly interval from 0 DAT to two weeks after harvest. In 2006, the recorded soil pH value was 5.42 at 0 DAT which started to increase up to 63 DAT (6.36) and then there was decreasing trend till harvest in the fields planted with Agni. In 2007, soil pH values increased from 5.36 (0 DAT) to 6.21 (42 DAT) and then decreased in the fields planted with Agni. Change in soil pH in the plots planted with Ranjit was also of similar nature like Agni with a fluctuation from 5.34 (0 DAT) to 6.32 (56 DAT) in 2006, and 5.36 (0 DAT) to 6.23 (49 DAT) in 2007, respectively.

4.2.7. Plant height (cm)

Plant height (cm) was recorded at weekly interval starting from 7 DAT till harvest (Table 4.5). Variation in height was observed in both the cultivars. Plant height increased up to 77 DAT in both Agni (137.63cm) and Ranjit (116.67cm) in 2006. Although there was increase in height in both the cultivars after 77 DAT, but the increment in height was at a slower rate. In 2007, increase in plant height was recorded up to 84 DAT in both Agni (129.20cm) and Ranjit (115.69cm). In both the years, Agni recorded significantly higher plant height compared to Ranjit.

4.2.8. Leaf number (hill^{-1})

Table 4.5 represents the leaf number per hill of Agni and' Ranjit'. At initial stage (7 DAT), the recorded leaf numbers were 10 and 9 hill^{-1} in Agni and Ranjit, respectively, which increased gradually to 130 hill^{-1} in Agni and 124 hill $^{-1}$ in Ranjit at 70 DAT in 2006. Subsequently, decrease in leaf number was noticed due to senescence and abscission of older leaves in both the cultivars. Similar trend was recorded in the year 2007. Agni recorded higher leaf number compared to Ranjit in both the years.

4.2.9. Leaf area (cm^2 hill^{-1})

Results of leaf area of Agni and Ranjit' are presented in Table 4.5. Leaf area recorded were 37.62cm^2 and 34.00cm^2 hill^{-1} in Agni and' Ranjit' respectively, in 2006 at 7 DAT, which increased gradually up to 1688.80cm^2 hill^{-1} in Agni and 1589.95cm^2 hill $^{-1}$ in Ranjit at 70 DAT. Subsequently, decrease in leaf area was observed due to senescence and abscission of older leaves in both the cultivars. In 2007, leaf area were 38.61cm^2 and 32.61cm^2 hill^{-1} at 7 DAT in cultivar Agni and Ranjit respectively, which increased gradually up to 1518.76cm^2 hill^{-1} in Agni and 1411.37cm^2 hill $^{-1}$ in Ranjit at 70 DAT. Cultivar Agni recorded significantly higher leaf area compared to Ranjit in both the years.

4.2.10. Leaf area index

Figure 4.16 represents the leaf area index of Agni and' Ranjit'. In both the years, leaf area index increased gradually and reached maximum at 70 DAT in the cultivars. Subsequently, decrease in leaf area index was observed towards the maturation of the crop. Agni recorded higher leaf area index compared to Ranjit in both the years.

4.2.11. Tiller number (hill^{-1})

Tiller number per hill of Agni and Ranjit were recorded at weekly interval and results are presented in Table 4.5. Variation in tiller number was observed in the cultivars in both the years. A gradual increase in tiller number per hill was noticed with the advancement of the growth. In 2006, the highest tiller number of 25 and 20 hill^{-1} was observed at 49 DAT in Agni and Ranjit, respectively. After attaining the highest value, both the cultivars showed a gradual decrease in tiller number per hill. In 2007, similar pattern of tiller development was recorded with the highest tiller number of 17.10 and 15.10 hill^{-1} at 63 DAT in Agni and Ranjit, respectively.

4.2.12. Root length (cm hill^{-1})

Figure 4.15 represents the root length (cm) of Agni and Ranjit. At initial stage (7 DAT), the root length were 135.38cm and 143.53cm in cultivar Agni and Ranjit respectively in 2006, which increased gradually up to 2861.96cm in Agni and 2371.06cm in Ranjit at 70 DAT and 63 DAT, respectively. Subsequently, gradual decrease in root length was observed till the harvest of the crop. In 2007, at 7 DAT, the root length were 144.61cm and 134.45cm in cultivar Agni and Ranjit respectively, and maximum of 2352.08cm in Agni and 2193.14cm in Ranjit was recorded at 70 DAT. Agni recorded significantly higher root length compared to Ranjit in both the years.

4.2.13. Root volume (ml hill^{-1})

Figure 4.15 represents the root volume (ml) per hill of Agni and' Ranjit'. In 2006, at 7 DAT, the recorded root volume were 1.83ml and 1.45ml in cultivar Agni and Ranjit respectively, which increased gradually up to 44.50ml in Agni and 35.38ml in Ranjit at 77

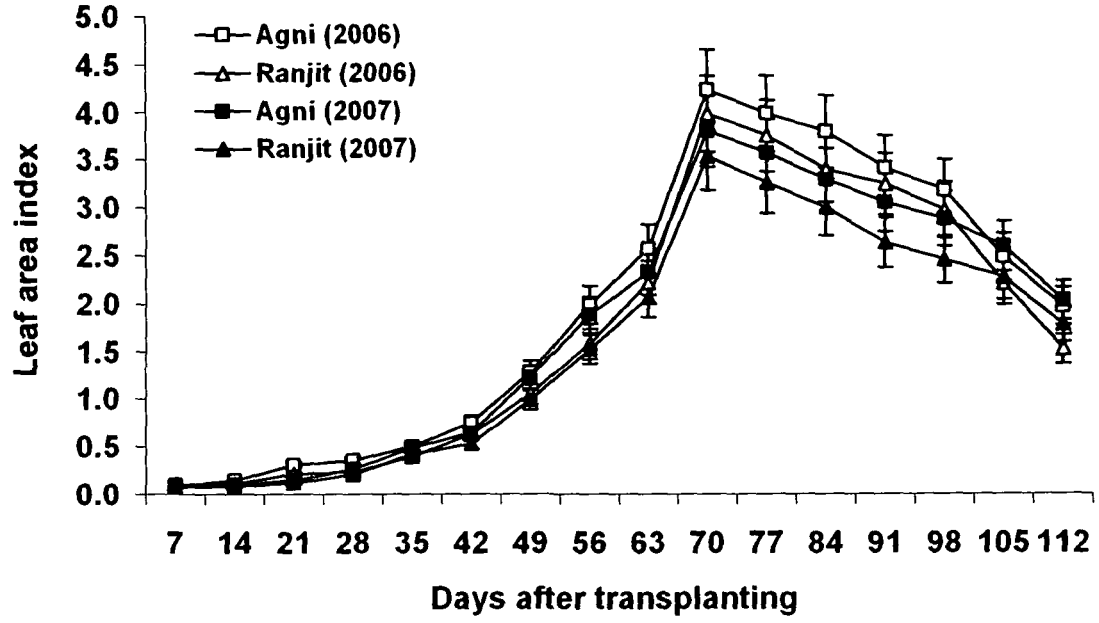


Fig. 4.16. Leaf area index of cultivars Agni and Ranjit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

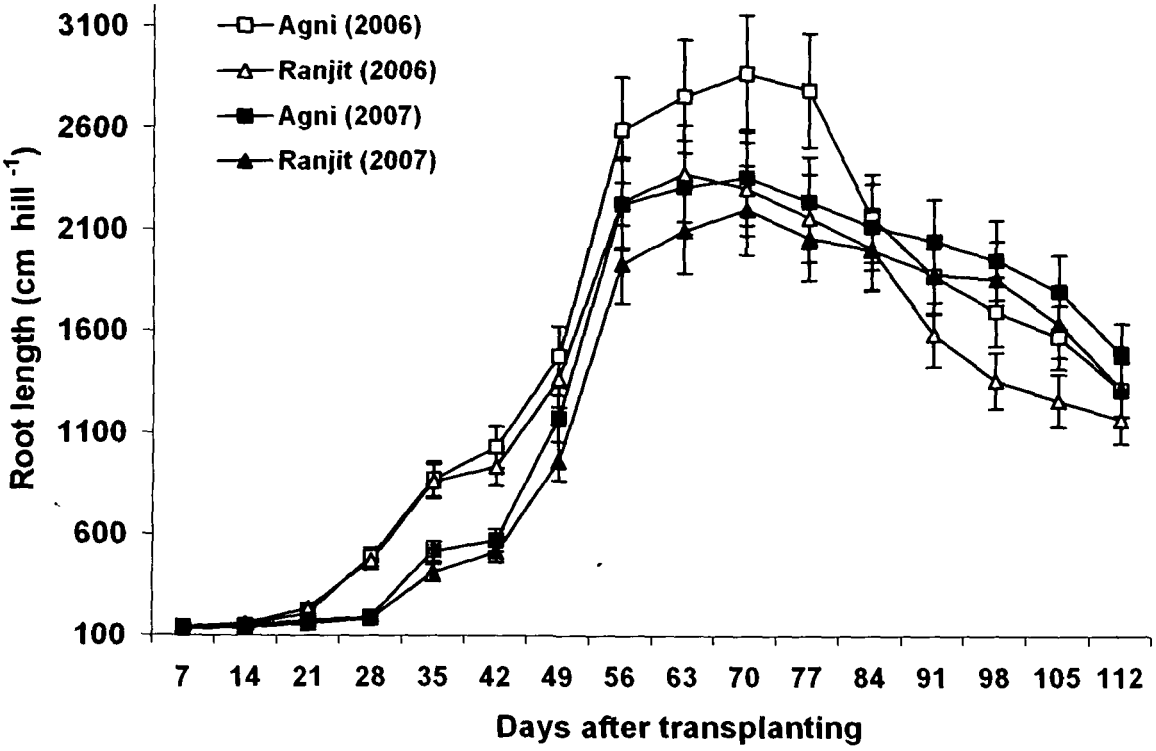


Fig. 4.17. Root length (cm hill^{-1}) of cultivars Agni and Ranjit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

DAT and 70 DAT, respectively. Subsequently, gradual decrease in root volume was recorded till the harvest of the crop. In 2007, at 7 DAT, root volumes were 1.60ml and 1.63ml in cultivar Agni and Ranjit respectively, and recorded 37.25ml in Agni and 30.50ml in Ranjit at 70 DAT. Agni recorded significantly higher root volume compared to Ranjit in both the years.

4.2.14. Leaf blade dry weight (g hill^{-1})

Table 4.6 represents the leaf blade dry weight (g) of Agni and Ranjit. In 2006, at 7 DAT, the recorded leaf blade dry weight were 0.19g and 0.17g in cultivar Agni and Ranjit respectively, which increased gradually to 10.08g in Agni and 9.85g in Ranjit at 70 DAT. Subsequently, gradual decrease in leaf blade dry weight was recorded till the harvest of the crop. In 2007, the recorded leaf blade dry weights were 0.19g and 0.16g in cultivar Agni and Ranjit respectively at 7 DAT, and obtained maximum of 9.11g in Agni and 7.20g in Ranjit at 70 DAT, respectively. Agni recorded higher leaf blade dry weight compared to Ranjit in both the years.

4.2.15. Leaf sheath dry weight (g hill^{-1})

Dry weights of leaf sheath of Agni and Ranjit were recorded at 7 days interval and data are presented in Table 4.6. In 2006, leaf sheath dry weights were 0.06g and 0.04g in cultivar Agni and Ranjit respectively at 7 DAT, which increased gradually to 9.08g in Agni and 3.09g in Ranjit at 84 DAT. Subsequently, gradual decrease in leaf sheath dry weight was recorded till the harvest of the crop. In 2007, at 7 DAT, the recorded leaf sheath dry weights were 0.08g and 0.06g in cultivar Agni and Ranjit respectively, and at 84 DAT the values were 4.41g in Agni and 3.40g in Ranjit, respectively. Agni recorded higher leaf sheath dry weight compared to Ranjit in both the years.

4.2.16. Culm dry weight (g hill^{-1})

Dry weights of culm (g) of the varieties Agni and Ranjit were recorded at 7 days interval and data are presented in Table 4.6. In 2006, culm dry weights were 0.15g and 0.09g in Agni and Ranjit respectively at 7 DAT, which increased gradually up to 11.42g in Agni and 9.14g in Ranjit at 105 DAT. In 2007, the recorded culm dry weight were 0.13g and 0.11g in Agni and Ranjit respectively at 7 DAT and maximum dry weights of culm were recorded 10.65g in Agni and 9.97g in Ranjit at harvest. Agni recorded higher culm dry weight compared to Ranjit in both the years.

4.2.17. Shoot dry weight (g hill^{-1})

Shoot dry weights (g) per hill of Agni and Ranjit were recorded at 7 days interval and data are presented in Table 4.6. In 2006, at 7 DAT, the shoot dry weights were 0.40g and 0.31g in cultivar Agni and Ranjit respectively, which increased gradually up to 22.44g in Agni and 19.90g in Ranjit at 70 DAT. Subsequently, gradual decrease in shoot dry weight was recorded till the harvest of the crop. In 2007, the recorded shoot dry weight were 0.40g and 0.33g in cultivar Agni and Ranjit respectively at 7 DAT, and recorded values of 21.67g in Agni and 18.44g in Ranjit at 77 DAT and 84 DAT, respectively were the maximum. Agni recorded higher shoot dry weight compared to Ranjit in both the years.

4.2.18. Root dry weight (g hill^{-1})

Figure 4.19 represents the root dry weight (g) of Agni and Ranjit. In 2006, at 7 DAT, the root dry weights were 0.08g and 0.07g in cultivar Agni and Ranjit respectively, which increased gradually and obtained maximum values of 3.89g in Agni and 2.97g in Ranjit at 70 DAT and 63 DAT, respectively. Subsequently, gradual decrease in root dry weight was

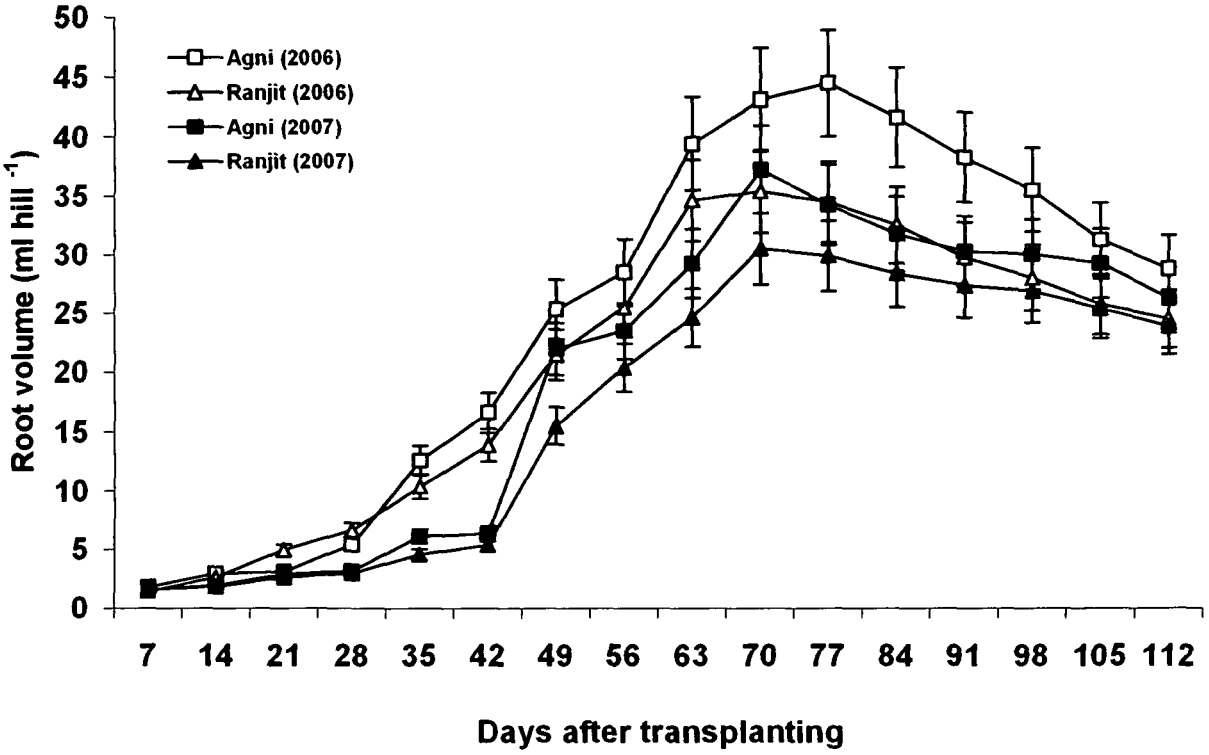


Fig. 4.18. Root volume (ml hill^{-1}) of cultivars Agni and Ranjit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

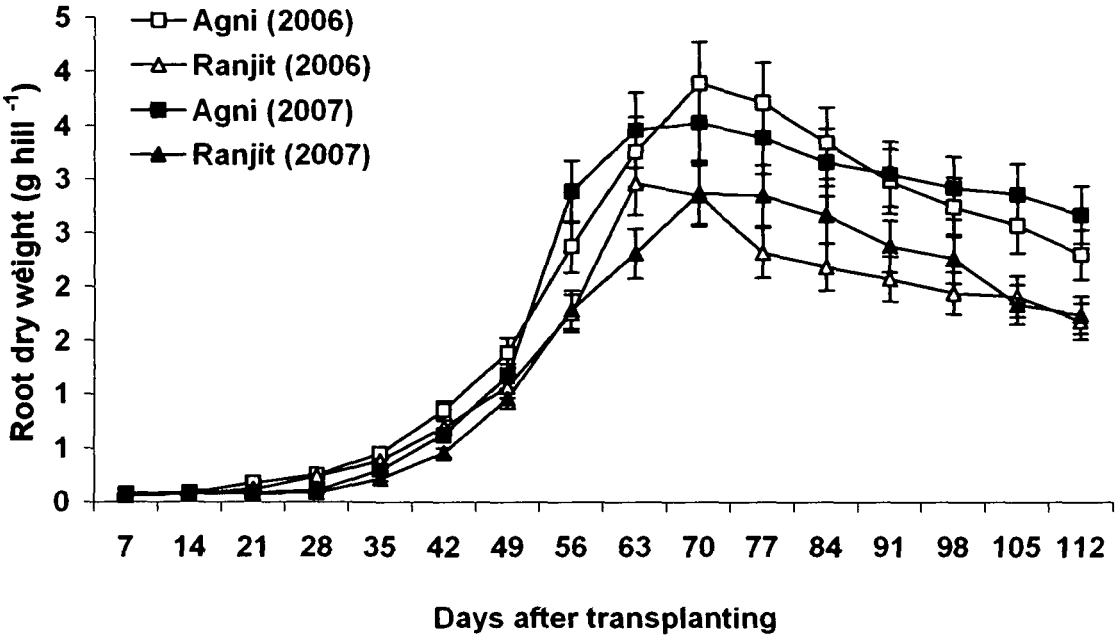


Fig. 4.19. Root dry weight (g hill^{-1}) of cultivars Agni and Ranjit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

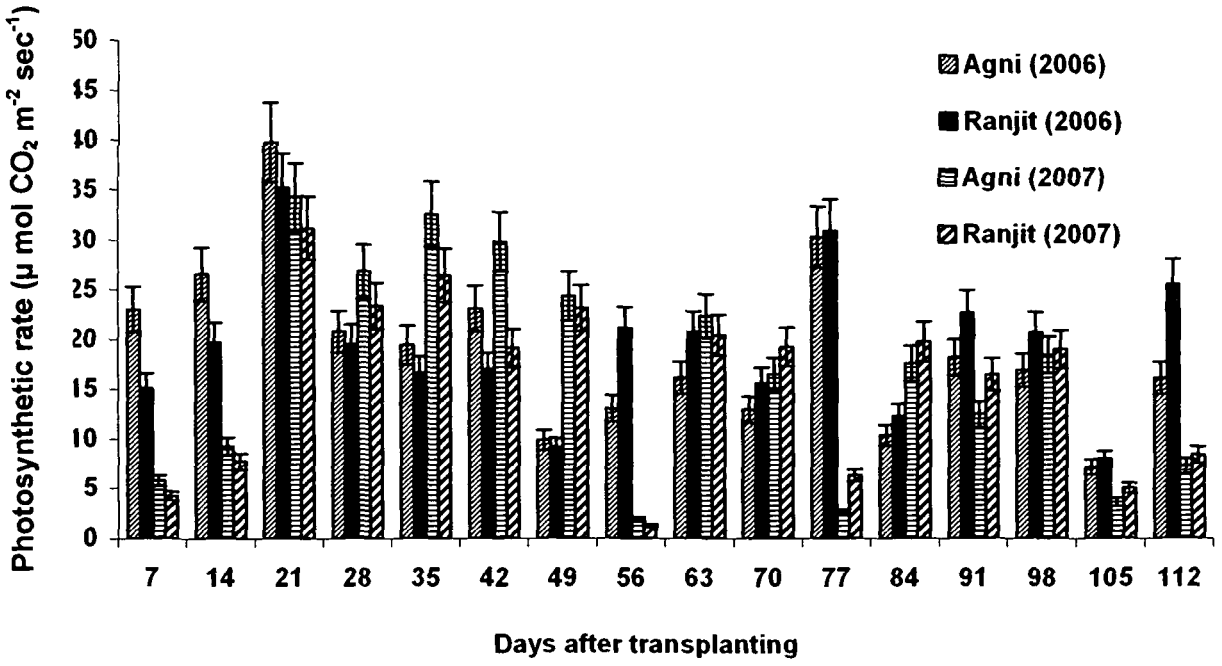


Fig. 4.20. Photosynthetic rate (μmol CO_2 m^{-2} sec^{-1}) of cultivars Agni and Ranjit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

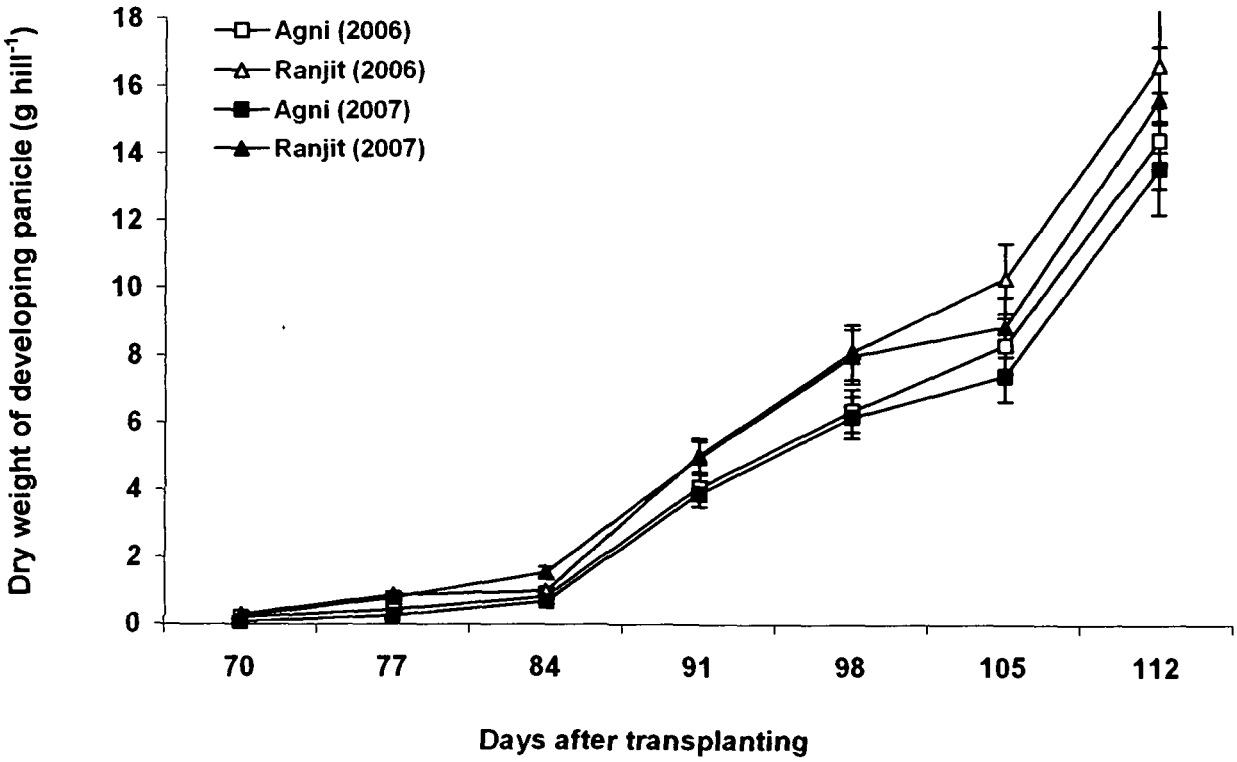


Fig. 4.21. Dry weight (g $hill^{-1}$) of developing panicle of cultivars Agni and Ranjit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

observed till the harvest of the crop. In 2007, at 7 DAT, the root dry weights were same (0.06g) in cultivar Agni and Ranjit, and obtained maximum values of 3.53g in Agni and 2.85g in Ranjit at 70 DAT. Agni recorded higher root dry weight compared to Ranjit in both the years.

4.2.19. Leaf photosynthetic rate (μ mol CO_2 m^{-2} sec^{-1})

Leaf photosynthetic rates (μ mol CO_2 m^{-2} sec^{-1}) of the two cultivars were recorded at weekly interval and values are presented in Figure 4.18. Significant cultivar differences in photosynthetic rate were observed. During the vegetative growth stage (up to 49 DAT in 2006; and up to 63 DAT in 2007), photosynthetic rate was higher in Agni, compared to Ranjit. However, during the reproductive stage (i.e. from 56 DAT in 2006; and from 70 DAT in 2007), photosynthetic rate was higher in variety Ranjit.

4.2.20. Dry weight of developing panicle (g $hill^{-1}$)

After panicle initiation, dry weights (g) of developing panicles of Agni and Ranjit were recorded at 7 days interval till harvest and values are presented in Figure 4.21. In 2006, the panicle dry weights were 0 21g and 0.29g in cultivar Agni and Ranjit respectively at 77 DAT, which increased gradually up to 14.37g in Agni and 16.60g in Ranjit, respectively at harvest. In 2007, the panicle dry weights were 0.08g and 0.24g in cultivar Agni and Ranjit respectively at 77 DAT, and were 13.52g in Agni and 15.57g in Ranjit, respectively at harvest. Ranjit recorded higher dry weight of developing panicle compared to Agni in both the years.

Table 4.7. Comparisons of yield and yield attributing parameters of cultivars Agni and Ranjit grown in irrigated / *Boro* ecosystem.

Cultivars / parameters	2006			2007		
	Agni	**Ranjit**	**t value**	**Agni**	**Ranjit**	**t value**
1000 grain weight (g)	19.13*	20.50*	2.52	18.30**	19.98**	6.69
Filled grain (%)	74.50**	78.50**	3.80	74.75^{NS}	77.50^{NS}	2.23
Panicle plant^{-1}	9.75^{NS}	10.50	1.70	9.75*	10.75*	2.45
Spikelet panicle^{-1}	87.25^{NS}	89.25^{NS}	2.19	86.75	88.75	2.19
Panicle (m $^{-2}$)	243.75^{NS}	262.50^{NS}	1.70	252.25^{NS}	261.50^{NS}	1.21
Panicle length (cm)	20.25*	22.00*	3.17	20.25*	21.50*	2.84
Panicle dry weight (g plant^{-1})	14.37**	16.60**	5.96	13.52**	15.57**	5.58
Yield (t ha^{-1})	3.03**	3.77**	4.06	2.99**	3.59**	5.45

* = Significant at 0.05 level of significance; ** = Significant at 0.01 level of significance; ^{NS} = Non significant

Table 4.8. Correlation between plant and soil parameters and methane emission from cultivars Agni and Ranjit grown in irrigated / *Boro* ecosystem.

	Correlation with methane emission			
	2006		2007	
Parameters	**Agni**	**Ranjit**	**Agni**	**Ranjit**
Plant height	NS	0.39*	NS	NS
Leaf No	0.51*	0.53*	0.58*	0.59*
Leaf area	NS	0.51*	NS	0.49*
LAI	NS	0.51*	NS	0.49*
Tiller No	0.70**	0.77**	0.67**	0.64**
Root length	0.70**	0.75**	0.55*	0.53*
Root volume	0.55*	0.61*	NS	NS
Root dry weight	0.50*	0.55*	NS	0.50*
Leaf blade dry weight	0.50*	0.53*	0.56*	0.51*
Leaf sheath dry weight	NS	NS	NS	NS
Culm dry weight	NS	NS	NS	NS
Shoot dry weight	NS	NS	NS	NS
Photosynthesis	NS	NS	NS	NS
Organic carbon	0.90**	0.88**	0.95**	0.96**
Soil pH	0.74**	0.67**	0.82**	0.80**
Soil temperature	NS	NS	NS	NS

* = Correlation is significant at the 0.05 level of significance
** = Correlation is significant at the 0.01 level of significance
NS = Non significant

4.2.21. Yield

Yield data and yield attributing parameters of the two cultivars are presented in Table 4.7. Variety Ranjit recorded significantly higher grain yield (2006: 3.77t ha^{-1}2007: 3.59t ha^{-1}) than Agni (2006: 3.03t ha^{-1}; 2007: 2.99t ha^{-1}) in both the years. Thousand grain weight (g $hill^{-1}$), filled grain (%), panicle $plant^{-1}$, spikelet $panicle^{-1}$, number of panicle (m^{-2}), panicle dry weight (g $hill^{-1}$) were also higher in Ranjit compared to Agni. Yield and yield development patterns in the varieties were similar in both the years.

4.3. Association of plant growth parameters with methane emission from rainfed upland / *Ahu* rice

4.3.1. Meteorological parameters

Figure 3.3 represents the meteorological parameter i.e. rainfall (mm) and air temperature (both maximum and minimum) in ^0C at weekly interval of the crop-growing season (April-July, 2006). Higher temperatures were recorded during the entire crop growing period. Pre-monsoon shower added to higher rainfall at initial stage (April-May) of crop growth.

4.3.2. Methane flux (mg m^{-2} hr^{-2})

Cultivar differences in methane emission (Fig. 4.22) were observed in the varieties Disang and Luit grown as rainfed crop. Higher seasonal integrated methane flux was recorded in variety Disang (E_{sif}: 1.38g m^{-2}), compared to Luit (E_{sif} : 0.96 g m^{-2}). Despite the cultivar differences in methane fluxes, a similar seasonal pattern of CH_4 emission from both the varieties was observed. Methane flux was initially very low, and then increased with the

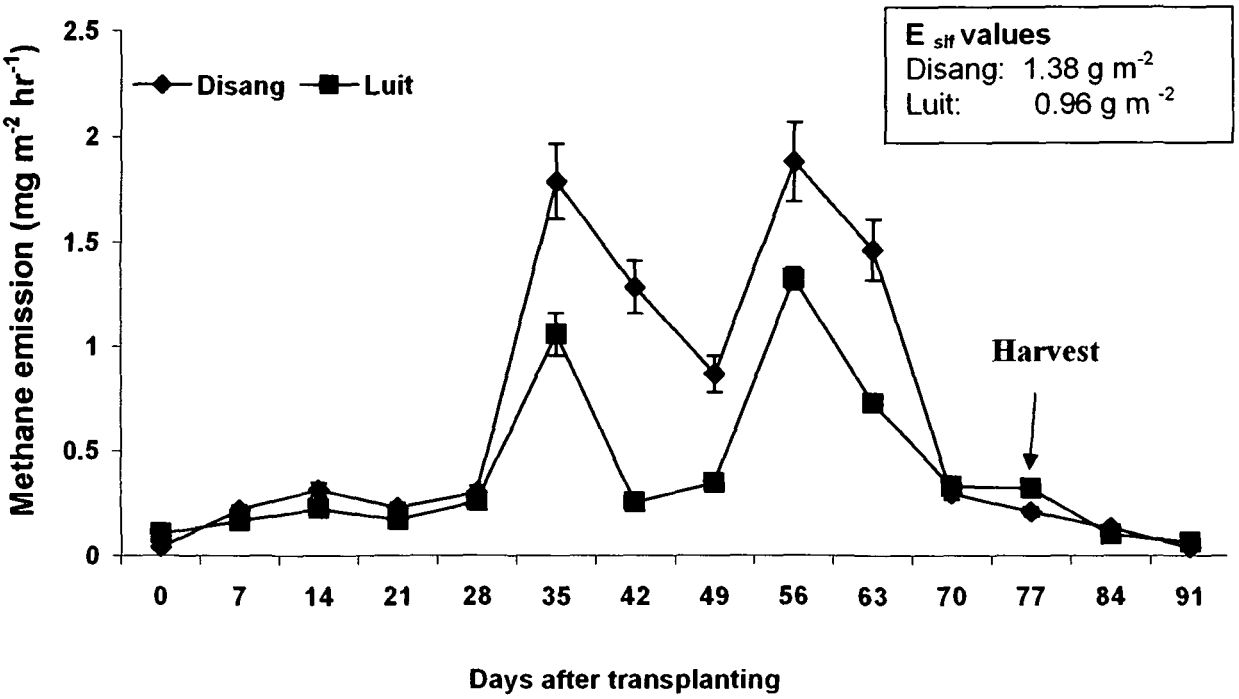


Fig. 4.22. Methane emission (mg m^{-2} hr^{-1}) from varieties Disang and Luit at different growth stages. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

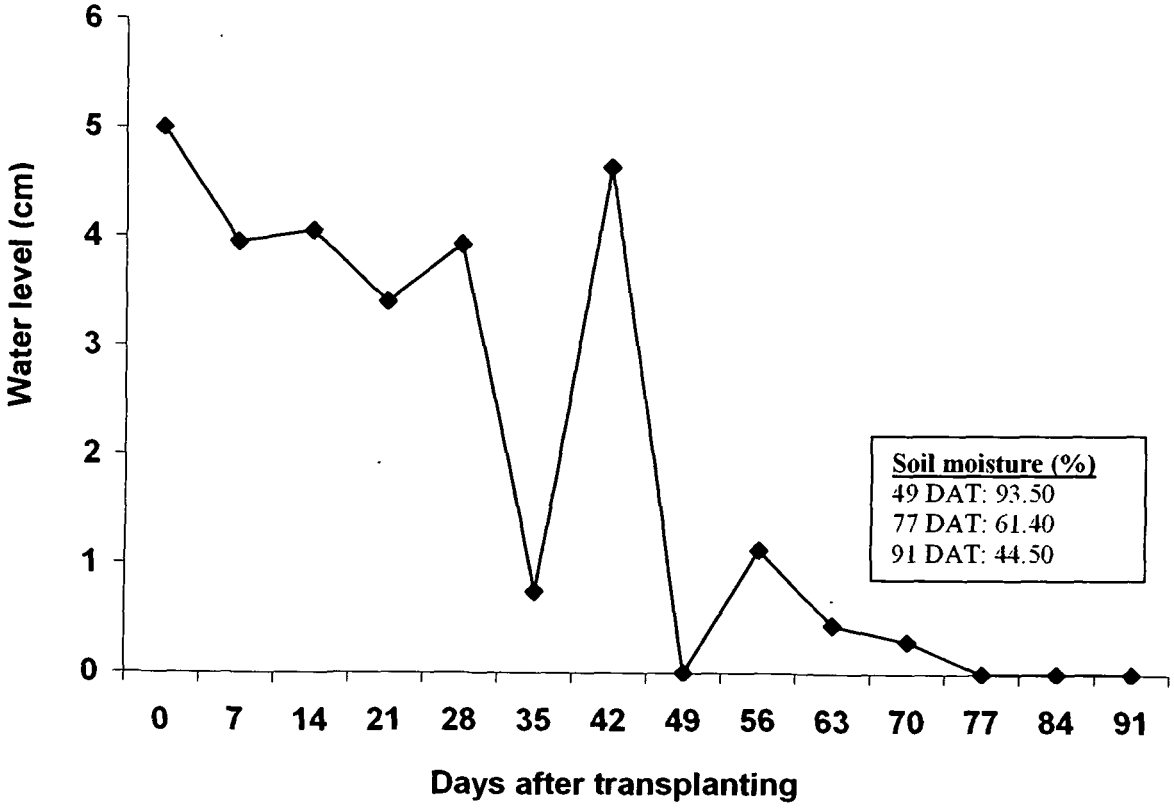


Fig. 4.23. Water level (cm) of the experimental field planted with varieties Disang and Luit.

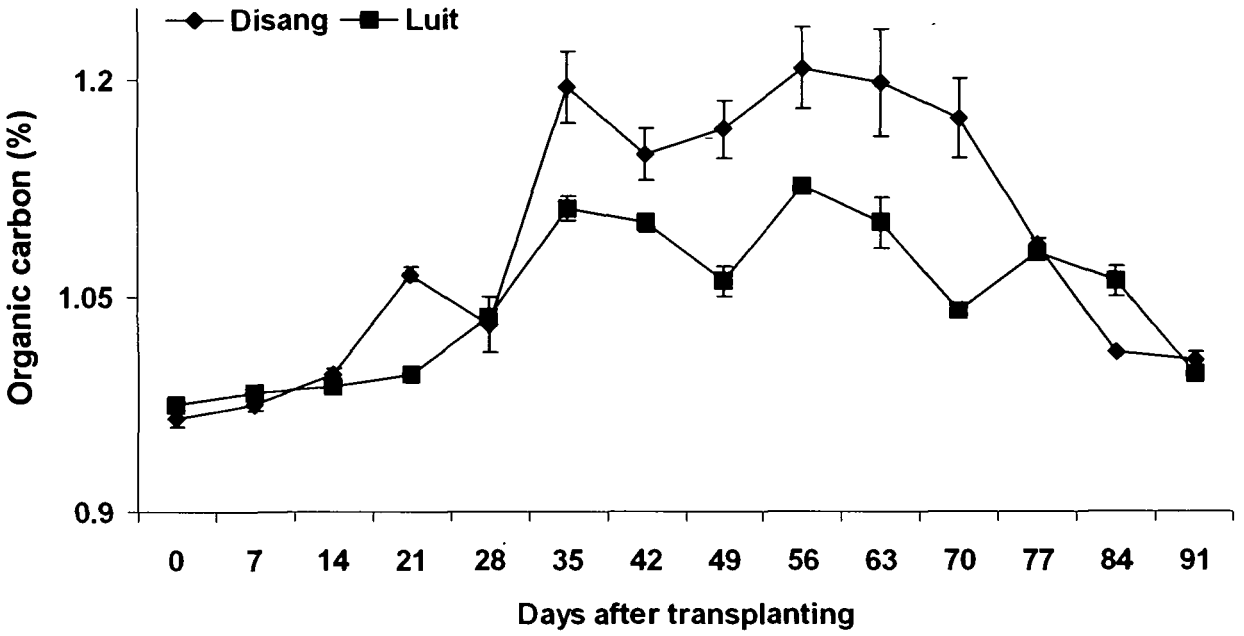


Fig. 4.24. Organic carbon (%) of soil of the experimental field (varieties Disang and Luit). Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

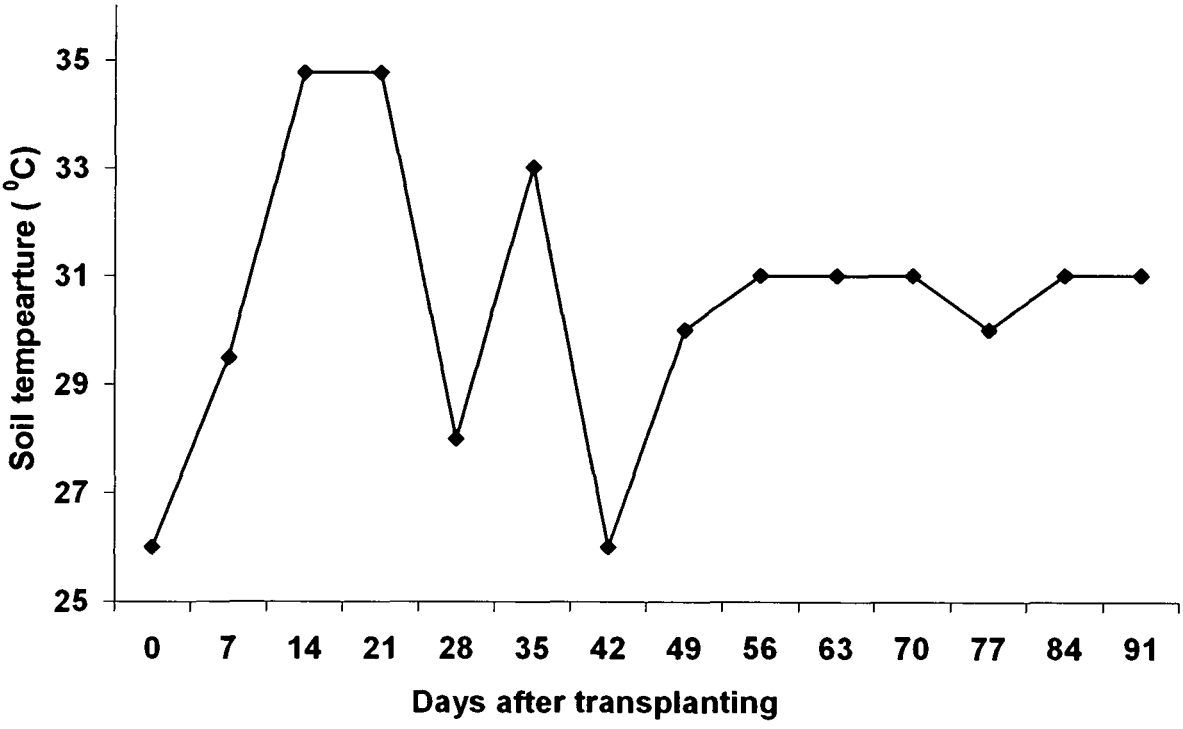


Fig. 4.25. Soil temperature (^{0}C) of the experimental field planted with varieties Disang and Luit.

advancing age of the rice plants. In both the varieties two distinct methane emission peaks were detected, one at active vegetative growth stage (1.79mg m^{-2} hr^{-2} in Disang and 1.15mg m^{-2} hr^{-2} in Luit at 35 DAT), and the other at panicle initiation stage (1.88mg $m^{-2}hr^{-2}$ in Disang and 1.32mg m^{-2} hr^{-2} in Luit at 56 DAT). Methane emission declined after panicle initiation stage in both the varieties and reduced to a negligible level at harvest.. Methane emission was negligible after harvest.

4.3.3. Water level (cm)

Water level (cm) in the experimental field was recorded at weekly interval and results are presented in Figure 4.23. Seasonal rainfall kept the experimental field submerged during most of the growth period, except at 49 days after transplanting and at harvest.

4.3.4. Soil organic carbon (%)

Soil organic carbon content (%) was initially low, reached maximum at active tillering and panicle initiation stage of the crop (Fig. 4.24). Similar trend was observed in both the plots grown with the two varieties. Higher soil organic carbon content was recorded in plots of Disang compared to Luit. Higher soil organic carbon content (%) was recorded at 35 DAT (1.20 in Disang and 1.11 in Luit) and 56 DAT (1.21 in Disang and 1.13 in Luit). A highly significant positive correlation was found between methane emission and soil organic carbon content (Table 4.11).

4.3.5. Soil temperature (°C)

Figure 4.25 represents the soil temperatures (°C) of the experimental fields recorded at weekly interval from the day of transplanting to two weeks after harvest. During the initial stage

of crop growth, higher soil temperature was recorded (34.74°C at 14 and 21 DAT). At harvest, the recorded soil temperature was 30°C.

4.3.6. Soil pH

Figure 4.26 represents the soil pH measured at weekly interval from day of transplanting to two weeks after harvest. The recorded soil pH value was 5.4 at 0 DAT in both the varieties. Soil pH started to increase up to 21 DAT (pH 6.3) and then there was a decreasing trend of soil pH till harvest (pH 5.5) in the fields planted with Disang. Fluctuation of soil pH in the plots with Luit was also of similar nature like Disang with a variation from 5.4 (0 DAT) to 6.2 (14 DAT) and again at harvest it was 5.4.

4.3.7. Plant height (cm)

Plant height (cm) of both the varieties was recorded at weekly interval till harvest (Table 4.9). There was variation in plant height in both the varieties. Rapid increase in plant height was recorded up to 56 DAT in both Disang (71.79cm) and Luit (81.95cm). Although there was increase in plant height in both the varieties after 56 DAT, but the increment in height was at a slower rate. Luit recorded significantly higher plant height compared to Disang from 28 DAT to harvest.

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

Table 4.9 represents the leaf number of the varieties Disang and Luit. At 7 DAT, the leaf numbers were 14.and 15 in variety Disang and Luit respectively, which increased gradually and the leaf number was 68 in Disang and 58 in Luit at 56 DAT. Subsequently,

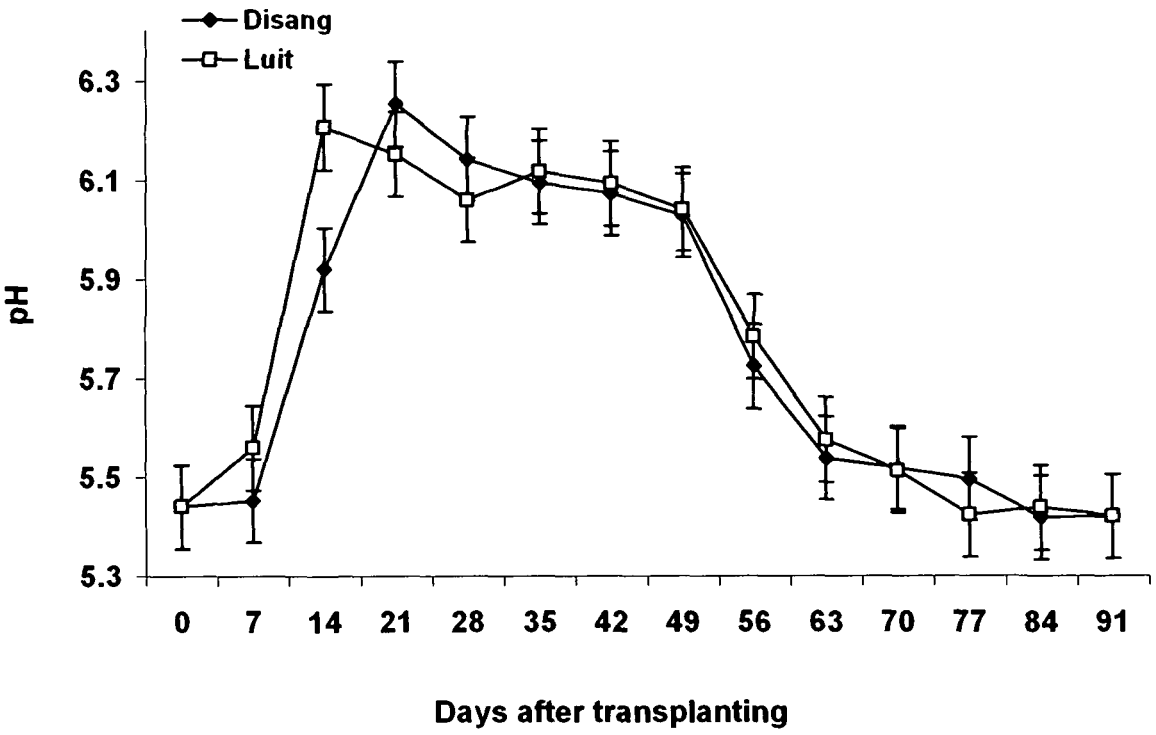


Fig. 4.26. Soil pH of the experimental field (varieties Disang and Luit). Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker.

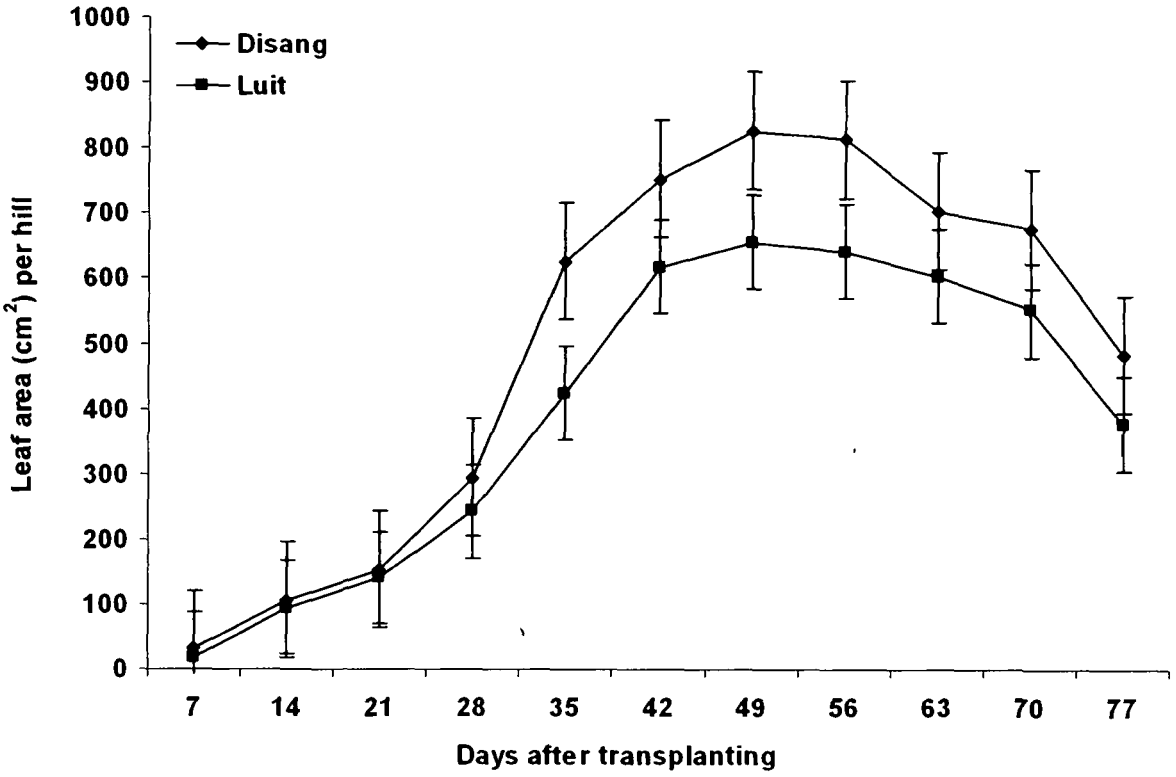


Fig. 4.27. Leaf area (cm^2 hill^{-1}) of varieties Disang and Luit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker)

decrease in leaf number was noticed due to senescence and abscission of older leaves in both the varieties. Disang recorded significantly higher leaf number compared to Luit from 14 DAT to harvest.

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

Figure 4.27 represents the leaf area (cm^2) per hill of Disang and Luit. At 7 DAT, the recorded leaf area were 30.95cm^2 and 16.43cm^2 in variety Disang and Luit respectively, which increased gradually up to 824.97cm^2 in Disang and 654.75cm^2 in Luit at 49 DAT. Subsequently there was decrease in leaf area. Disang recorded higher leaf area compared to Luit.

4.3.10. Leaf area index

Table 4.9 represents the leaf area index of Disang and Luit. Leaf area index increased gradually and was maximum (2.06 in Disang and 1.64 in Luit) at 49 DAT in both the varieties. Decrease in leaf area index was observed towards the maturation of the crop. Disang had a higher leaf area index compared to Luit.

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

Tiller number per hill of Disang and Luit were recorded at weekly interval and presented in Table 4.9. Significant variation in tiller number was observed between the two varieties. A gradual increase in tiller number per hill was noticed with the advancement of growth and development of the crop. The highest tiller number of 15 and 13 $hill^{-1}$ was observed at 42 DAT in Disang and Luit, respectively. And thereafter there was gradual decrease in tiller number per hill in both the varieties. Disang recorded significantly higher tiller number compared to Luit.

Table 4.9. Comparison of plant height, leaf number, tiller number and dry weights of leaf-blade, leaf-sheath and culm (hill^{-1}) between varieties Disang and Luit grown in rainfed upland / *Ahu* ecosystem.

		Days after transplanting										
		7	14	21	28	35	42	49	56	63	70	77
Plant height (cm)	Disang	25 63**	28 30^{NS}	42 56^{NS}	48 58**	53 26**	61 17**	67 27**	71 79**	71 94**	72 25**	72 47**
	Luit	23 46**	28 64^{NS}	42 10^{NS}	52 21**	57 22**	66 21**	77 15**	81 95**	82 13**	82 43**	82 62**
	t values	4 322	0 055	0 256	7 787	10 042	7 688	16 393	17 208	18 015	18 049	18 416
Leaf number (hill^{-1})	Disang	14 50^{NS}	25 92**	34 75**	59 03**	61 28**	62 95**	67 13**	68 30**	63 68**	59 88**	45 58**
	Luit	14 83^{NS}	20 92**	28 83**	51 35**	54 10**	55 60**	57 43**	57 65**	53 05**	49 05**	35 05**
	t values	0 177	3 900	3 875	27 757	16 579	19 471	12 797	22 836	23 479	28 448	20 390
Leaf area index	Disang	0 08**	0 27**	0 38**	0 74**	1 56**	1 88**	2 06**	2 03**	1 75**	1 69**	1 20**
	Luit	0 04**	0 24**	0 35**	0 61**	1 06**	1 54**	1 64**	1 60**	1 50**	1 38**	0 94**
	t values	6 784	3 175	3 838	20 527	54 69	24 739	22 029	29 251	23 779	17 797	11 396
Tiller number (hill^{-1})	Disang	2 25^{NS}	6 42^{NS}	12 67*	14 33**	14 83**	15 23**	14 68**	14 25**	13 25**	12 43**	11 33**
	Luit	2 50^{NS}	4 83^{NS}	11 75*	13 30**	13 50**	13 58**	13 58**	13 33**	12 28**	11 53**	10 30**
	t values	1 964	2 165	3 667	5 704	8 020	16 855	10 914	10 262	14 085	9 194	7 137
Leaf blade dry weight (g hill^{-1})	Disang	0 095^{NS}	0 675^{NS}	0 933**	2 596**	3 953**	5 959**	8 932**	9 958**	9 468**	9 331**	8 639**
	Luit	0 096^{NS}	0 68^{NS}	0 819**	2 096**	3 071**	4 944**	7 879**	8 922**	9 073**	8 870**	7 550**
	t values	0 570	0 504	25 828	22 683	37 344	34 397	23 067	40 694	8 083	10 341	14 984
Leaf sheath dry weight (g hill^{-1})	Disang	0 094**	0 106^{NS}	0 441^{NS}	2 661**	3 561**	6 077**	9 032**	9 700**	9 511**	9 353**	9 249**
	Luit	0 096**	0 115^{NS}	0 407^{NS}	2 073**	3 061**	5 037**	8 391**	9 260**	9 367**	8 849**	8 226**
	t values	0 812	2 262	3 969	12 791	18 969	34 927	19 665	17 409	7 307	17 153	28 505
Culm dry weight (g hill^{-1})	Disang	0 083^{NS}	0 134^{NS}	0 260**	0 656^{NS}	0 921**	1 385**	3 268**	3 472**	3 505**	3 546^{NS}	3 579^{NS}
	Luit	0 086^{NS}	0 137^{NS}	0 206**	0 671^{NS}	0 772**	1 083**	2 635**	3 096**	3 385**	3 507^{NS}	3 533^{NS}
	t values	0 696	1 145	11 085	0 807	4 605	11 950	10 896	5 330	5 993	1 888	2 282
Shoot dry weight (g hill^{-1})	Disang	0 27^{NS}	0 92^{NS}	1 63**	5 91**	8 44**	13 42**	21 23**	23 13**	22 48**	22 23**	21 47**
	Luit	0 28^{NS}	0 93^{NS}	1 43**	4 84**	6 90**	11 06**	18 91**	21 28**	21 83**	21 23**	19 31**
	t values	1 213	1 093	17 254	15 104	27 851	103 808	28 582	25 252	9 208	11 728	17 827

* = Significant at 5% level of significance, ** = Significant at 1% level of significance, ^{NS} = Non significant.

4.3.12. Root length (cm hill^{-1})

Figure 4.28 represents the root length (cm) per hill of Disang and Luit. At 7 DAT, the recorded root length were 183.80cm and 149.10cm in variety Disang and Luit respectively, which increased gradually and obtained values of 1329.00cm in Disang and 1165.00cm in Luit at 63 DAT.. Subsequently, gradual decrease in root length was observed till the harvest of the crop. Disang recorded significantly higher root length compared to Luit.

4.3.13. Root volume (ml hill^{-1})

Figure 4.29 represents the root volume (ml) per hill of Disang and Luit. At initial stage (7 DAT), the recorded root volume were 0.27ml and 0.13ml in variety Disang and Luit respectively, which increased gradually up to 3.28ml in Disang and 2.35ml in Luit at 63 DAT and 70 DAT, respectively. Subsequently there was gradual decrease in root volume till the harvest of the crop. Disang recorded higher root volume compared to Luit

4.3.14. Leaf blade dry weight (g hill^{-1})

Table 4.9 represents the leaf blade dry weight (g) of Disang and Luit. At initial stage (7 DAT), the recorded leaf blade dry weight were 0.10g and 0.10g in variety Disang and Luit respectively, which increased gradually to record maximum values of 9.96g in Disang and 9.07g in Luit at 56 DAT and 63 DAT, respectively. There was gradual decrease in leaf blade dry weight till the harvest of the crop. Disang recorded higher leaf blade dry weight compared to Luit.

4.3.15. Leaf sheath dry weight (g hill^{-1})

Dry weight of leaf sheath of Disang and Luit was recorded at 7 days interval and data are presented in Table 4.9. At initial stage (7 DAT), the recorded leaf sheath dry weight were 0.09g and 0.10g in variety Disang and Luit respectively, which increased gradually up to 9.70g in Disang and 9.70g in Luit at 56 DAT and 63 DAT, respectively. Subsequently, gradual decrease in leaf sheath dry weight was recorded till the harvest of the crop. Disang recorded higher leaf sheath dry weight compared to Luit in both the years.

4.3.16. Culm dry weight (g hill^{-1})

Dry weight of culm (g) per hill of Disang and Luit was recorded at 7 days interval and data are presented in Table 4.9. The culm dry weights were 0.08g and 0.09g in variety Disang and Luit respectively at 7 DAT, which increased gradually up to 3.58g in Disang and 3.53g in Luit at harvest. Disang recorded higher culm dry weight compared to Luit.

4.3.17. Shoot dry weight (g hill^{-1})

Shoot dry weight (g) per hill of Disang and Luit was recorded at 7 days interval and data are presented in Table 4.9. At 7 DAT, the recorded shoot dry weights were 0.27g and 0.28g in variety Disang and Luit respectively, which increased gradually up to 23.13g in Disang at 56 DAT, and 21.83g in Luit at 63 DAT. Subsequently, gradual decrease in shoot dry weight was recorded till the harvest of the crop. Disang recorded higher shoot dry weight compared to Luit.

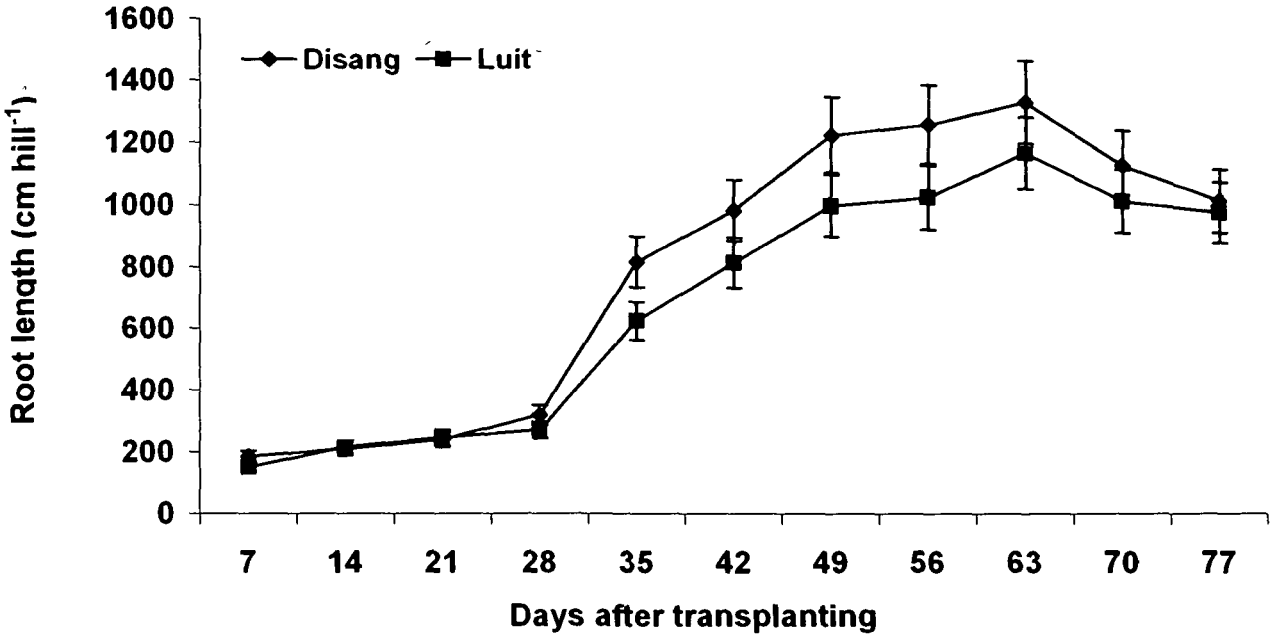


Fig. 4.28. Root length (cm hill^{-1}) of varieties Disang and Luit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

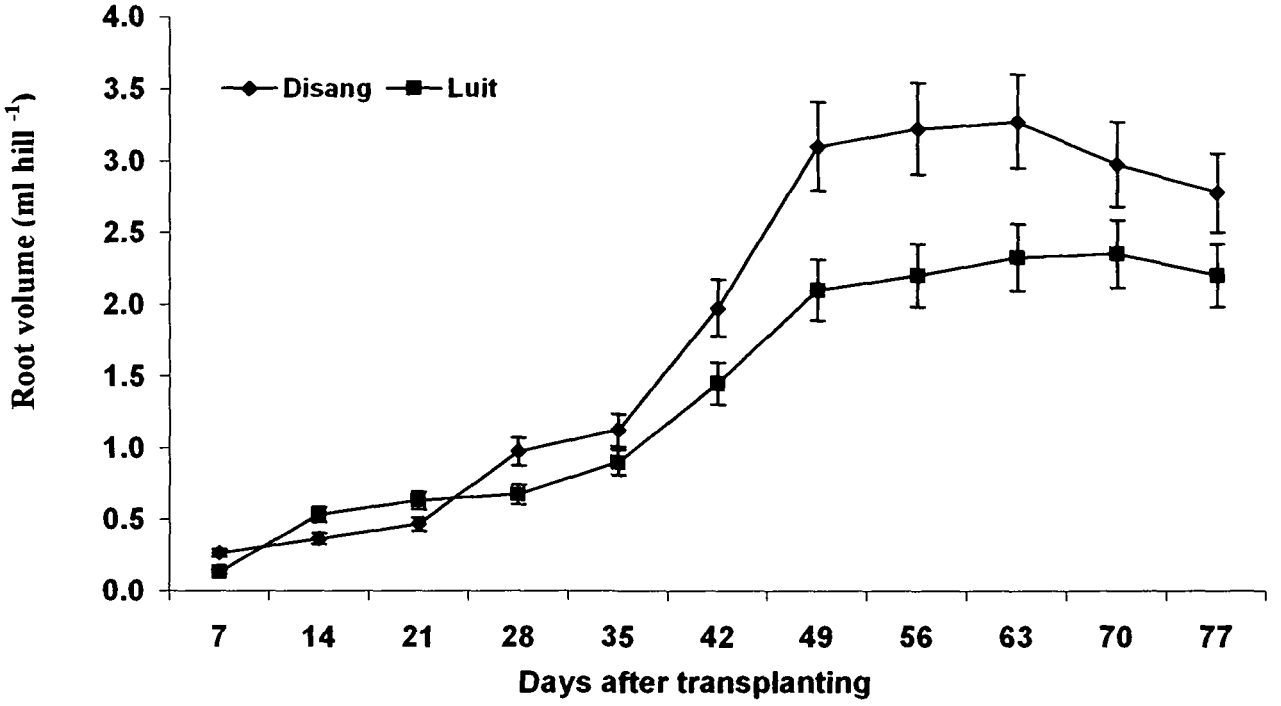


Fig. 4.29. Root volume (ml hill^{-1}) of varieties Disang and Luit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

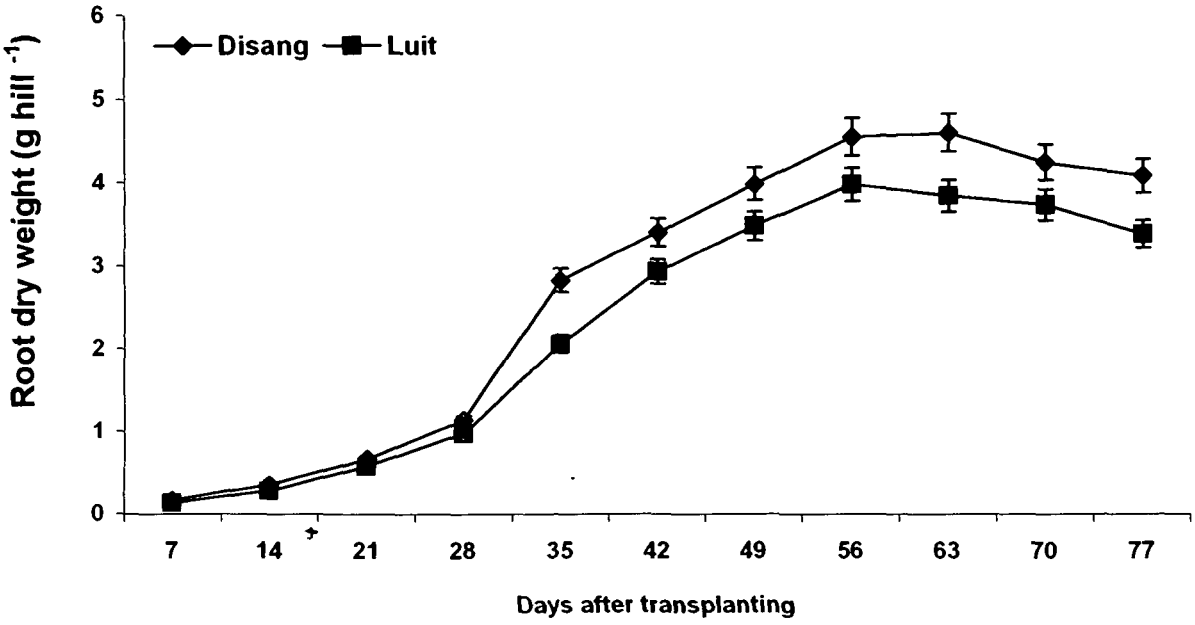


Fig. 4.30. Root dry weight (g hill^{-1}) of varieties Disang and Luit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

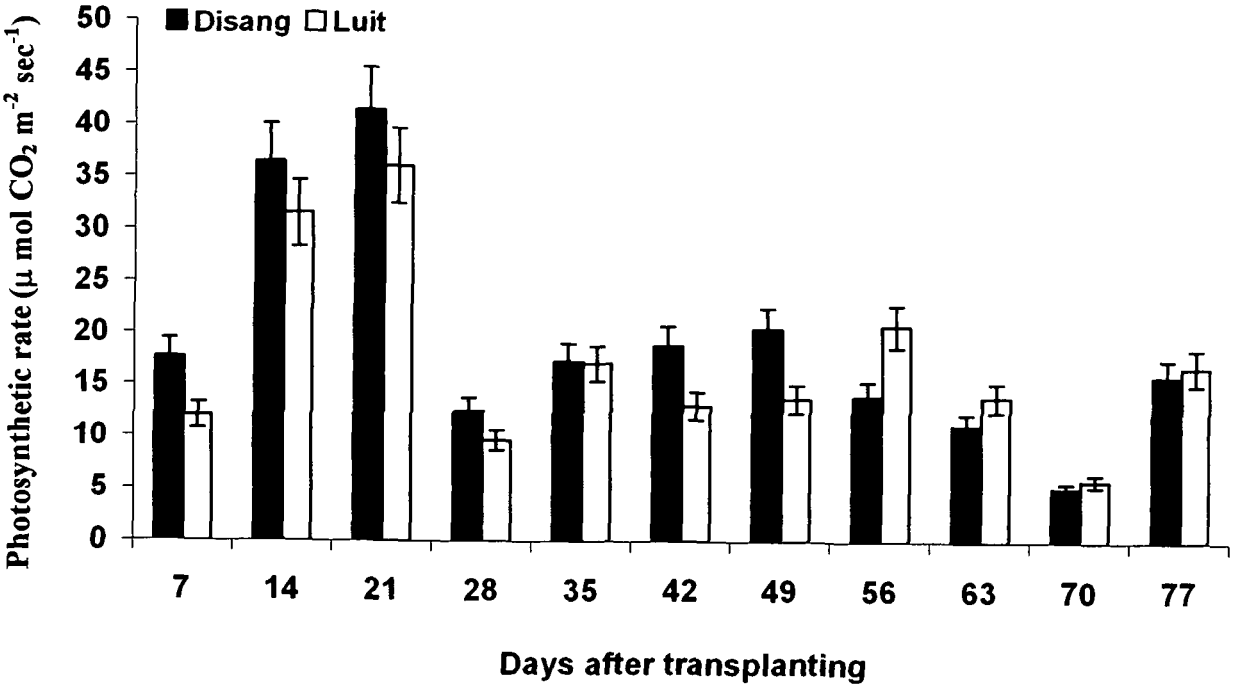


Fig. 4.31. Photosynthetic rate (μmol CO_2 m^{-2} sec^{-1}) of varieties Disang and Luit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

4.3.18. Root dry weight (g hill^{-1})

Figure 4.30 represents the root dry weight (g) of Disang and Luit. At 7 DAT, the root dry weights were 0.17g and 0.14g in variety Disang and Luit respectively, and then it started to increase up to 4 57g in Disang and 3.95g in Luit at 63 DAT and 56 DAT, respectively. Subsequently there was gradual decrease in root dry weight till the harvest of the crop. Disang recorded higher root dry weight compared to Luit.

4.3.19. Leaf photosynthetic rate (μ mol CO_2 m^{-2} sec^{-1})

Leaf photosynthetic rates (μ mol CO_2 m^{-2} sec^{-1}) of the two varieties were recorded at weekly interval and data are presented in Figure 4.31. During the vegetative growth phase (up to 49 day after transplanting) higher photosynthetic rate was recorded in Disang, compared to Luit. However, from the panicle initiation stage (i.e from 56 day after transplanting), higher photosynthetic rate was recorded in Luit.

4.3.20. Dry weight of developing panicle (g hill^{-1})

After panicle initiation, dry weights (g) of developing panicles per hill of Disang and Luit were recorded at 7 days interval till harvest and values are presented in Figure 4.32. At 49 DAT, the panicle dry weights were 0.27g and 0.29g hill^{-1} in variety Disang and Luit respectively, which increased gradually and obtained values of 11.56g hill^{-1} in Disang and 12.61g hill $^{-1}$ in Luit, respectively at harvest. Luit recorded higher dry weight of developing panicle compared to Disang in both the years.

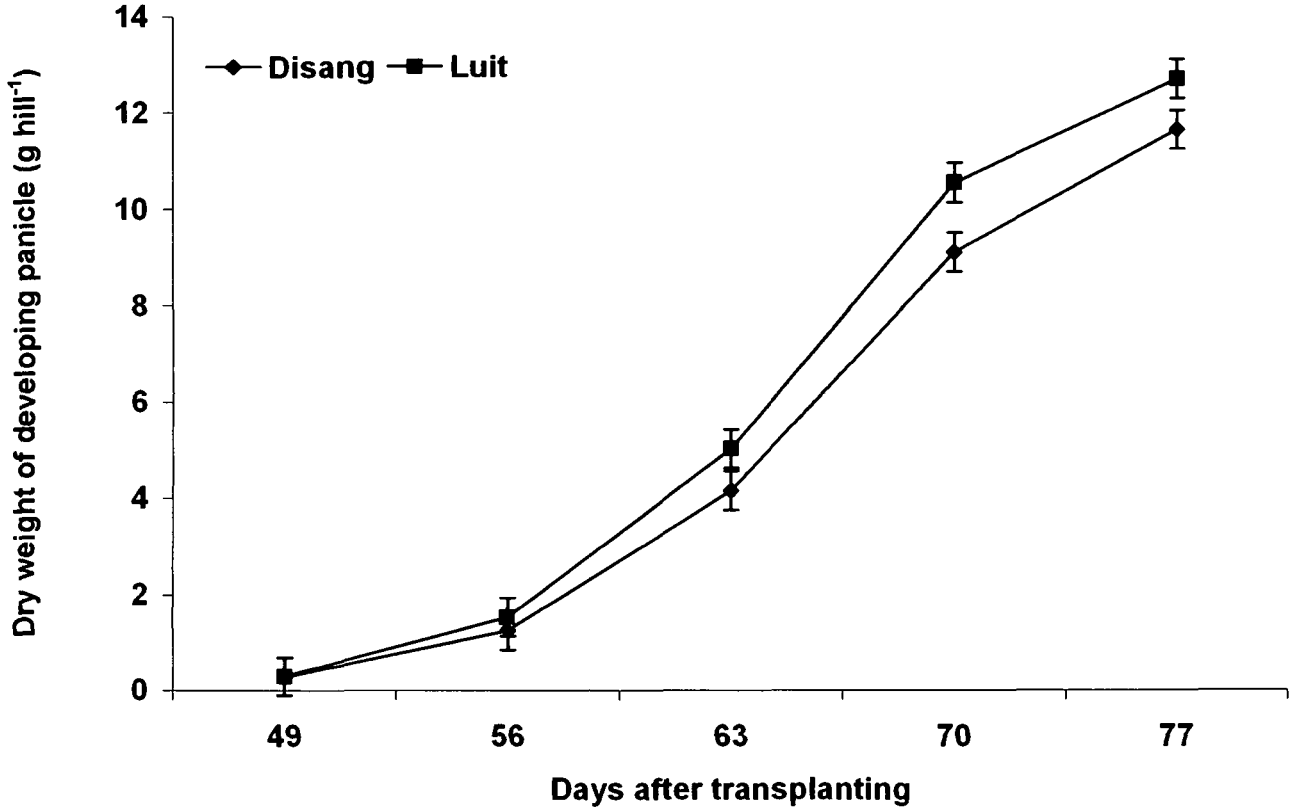


Fig. 4.32. Dry weight (g hill^{-1}) of developing panicle of varieties Disang and Luit. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10. When no bars visible, they are completely covered by the marker).

Table 4.10.Comparisons of yield and yield attributing parameters of varieties Disang and Luit grown in rainfed upland / *Ahu* ecosystem.

Parameters	Variety		
	Luit	**Luit**	**t values**
1000 grain weight (g)	19.00a*	20.25b*	3.286
Spikelet sterility (%)	14.00a*	12.87b*	2.742
Panicle plant^{-1}	9.33a**	11.03b**	14.20
Spikelet panicle^{-1}	72.94a	73.31a	0.898
Panicle (m $^{-2}$)	234.00a*	236.00b*	2.449
Panicle length (cm)	20.20a**	21.98b**	4.219
Panicle dry weight (g plant^{-1})	11.56a**	12.61b**	3.962
Yield (t ha^{-1})	2.78a**	2.99b**	12.86

In each row, means with similar letters are not significantly different.
(* = Significant at 0.05 level of significance; ** = Significant at 0.01 level of significance).

Table 4.11. Correlation of plant and soil parameters with methane emission from varieties Disang and Luit grown in rainfed upland / *Ahu* ecosystem.

Parameters	Correlation with methane emission	
	Disang	**Luit**
Plant Height	0.44*	0.44*
Leaf number	0.66*	0.55*
Tiller Number	0.54*	0.43*
Leaf Area	0.71**	0.51*
Root Volume	0.43*	NS
Root length	0.61*	0.48*
Root dry weight	0.56*	0.50*
Leaf-blade dry weight	0.45*	0.45*
Leaf-sheath dry wt	0.42*	0.45*
Culm dry weight	NS	NS
Photosynthesis	NS	NS
Organic carbon	0.78**	0.75**
Soil pH	NS	NS
Soil temperature	NS	NS

*= Correlation is significant at the 0.05 level of significance

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

NS = Non significant

4.3.21. Yield

Data recorded on yield and yield attributing parameters of the two varieties are presented in Table 4.10. Variety Luit recorded significantly higher grain yield (2.99t ha^{-1}) than Disang (2.78t ha^{-1}). Thousand grain weight (g $hill^{-1}$), filled grain (%), panicle $plant^{-1}$, spikelet $panicle^{-1}$, number of panicle (m^{-2}), panicle dry weight (g $hill^{-1}$) were also higher in Luit compared to Disang.

4.4. Analysis of intervarietal difference in methane flux from rice plants grown during monsoon season as biological mitigation option

4.4.1. Meteorological parameters

Figure 3.3 represents the meteorological parameter i.e. rainfall (mm) and air temperature (both maximum and minimum) in ^0C at weekly interval of the crop-growing season. Higher temperatures were recorded during the initial stage of the crop growing period (July- September). There was gradual drop in temperatures towards the end of the crop growing season (November- December).

4.4.2. Methane flux (mg m^{-2} hr^{-2}) and seasonal integrated methane flux (g m^{-2})

Measurement of CH_4 fluxes from ten rice cultivars exhibited significant cultivar differences in CH_4 emission (Fig. 4.33; Table 4.12). Highest seasonal integrated CH_4 flux (E_{sif}) was recorded from the cultivar Basmuthi (E_{sif}: 12.46g m^{-2}) and lowest from Gitesh (E_{sif} : 8.74g m^{-2}) (Fig. 4.34). The tested rice cultivars were ranked into three groups based on their E_{sif} values as high methane emitting (cultivars: Basmuthi, Bogajoha, Choimora), medium level methane emitting (cultivars: Rashmisali, Lalkalomdani, Mahsuri and

Moniram) and low CH_4 emitting cultivars (cultivars: Kushal, Prafulla and Gitesh). In all the cases, CH_4 flux was initially very low, and then increased with the advancing age of the rice plants. Two distinct CH_4 emission peaks were observed in each genotype, one at active tillering stage, and the other at panicle initiation stage, irrespective of high, medium and low CH_4 emitting cultivars. First emission peak was observed at 42 DAT in cultivars Choimora, Rashmisali, Lalkalomdani and Kushal; at 49 DAT in Basmuthi, Mahsuri, Prafulla and Gitesh; and at 56 DAT in cultivar Bogajoha and Moniram, which corresponded to the active tillering stage of the crop. Second CH_4 emission peak was found at 63 DAT in cultivar Rashmisali; at 70 DAT in Basmuthi, Choimora, Lalkalomdani, Mahsuri and Kushal; and at 77 DAT in cultivar Bogajoha, Moniram, Prafulla and Gitesh, at panicle initiation stage. The rate of CH_4 emission declined after panicle initiation stage in all the cultivars and reduced to a negligible level at harvest.

4.4.3. Water level (cm)

Water level (cm) in the experimental field was recorded at weekly intervals and results are presented in Figure 4.35. Water level in the field was highest (4.6cm) at 63 DAT.

4.4.4. Soil organic carbon (%)

Organic carbon content (%) of soil was initially low, reached maximum at active tillering and panicle initiation stage (Table 4.13) of the crop. At the end of the crop growth period, the organic carbon in the soil was low. A highly significant positive correlation was found between methane emission and soil organic carbon (Table 4.22).

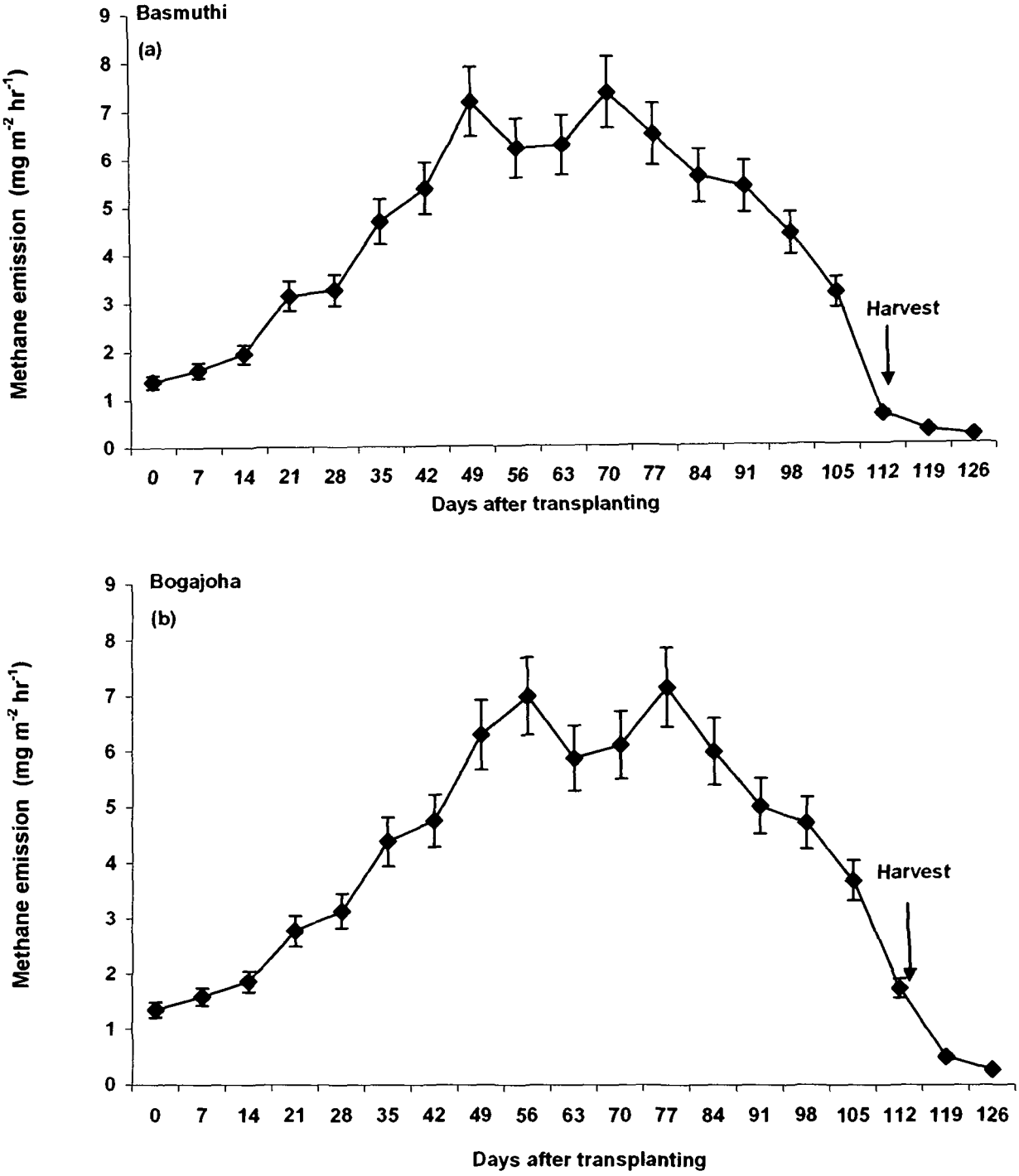


Fig. 4.33. (a) and (b). Methane emission (mg m^{-2} hr^{-1}) from cultivars Basmuthi and Bogajoha grown in monsoon / *Sali* ecosystem. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10). When no bars visible, they are completely covered by the marker.

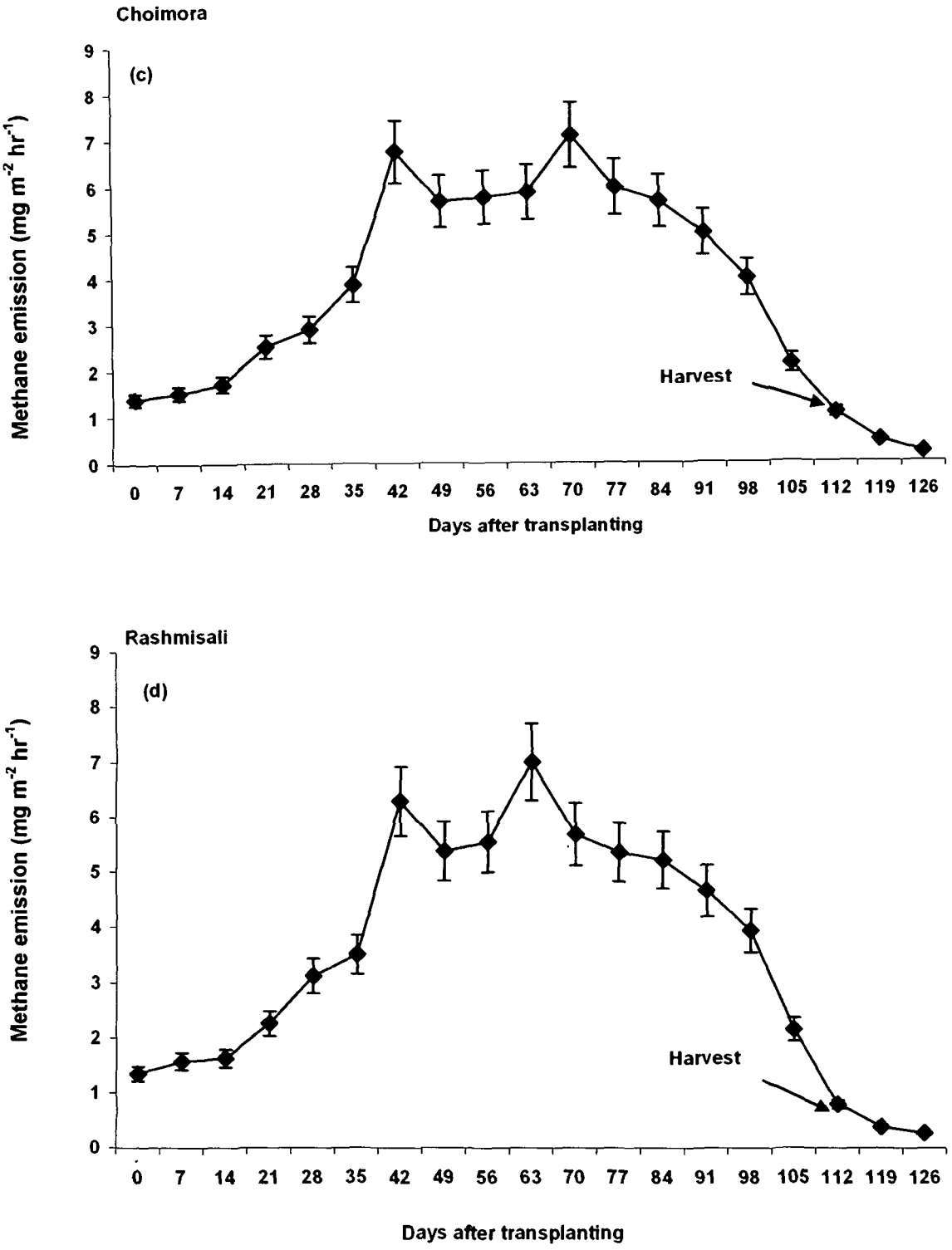


Fig. 4.33. (c) and (d). Methane emission (mg m^{-2} hr^{-1}) from cultivars Choimora and Rashmisali grown in monsoon / *Sali* ecosystem. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10). When no bars visible, they are completely covered by the marker.

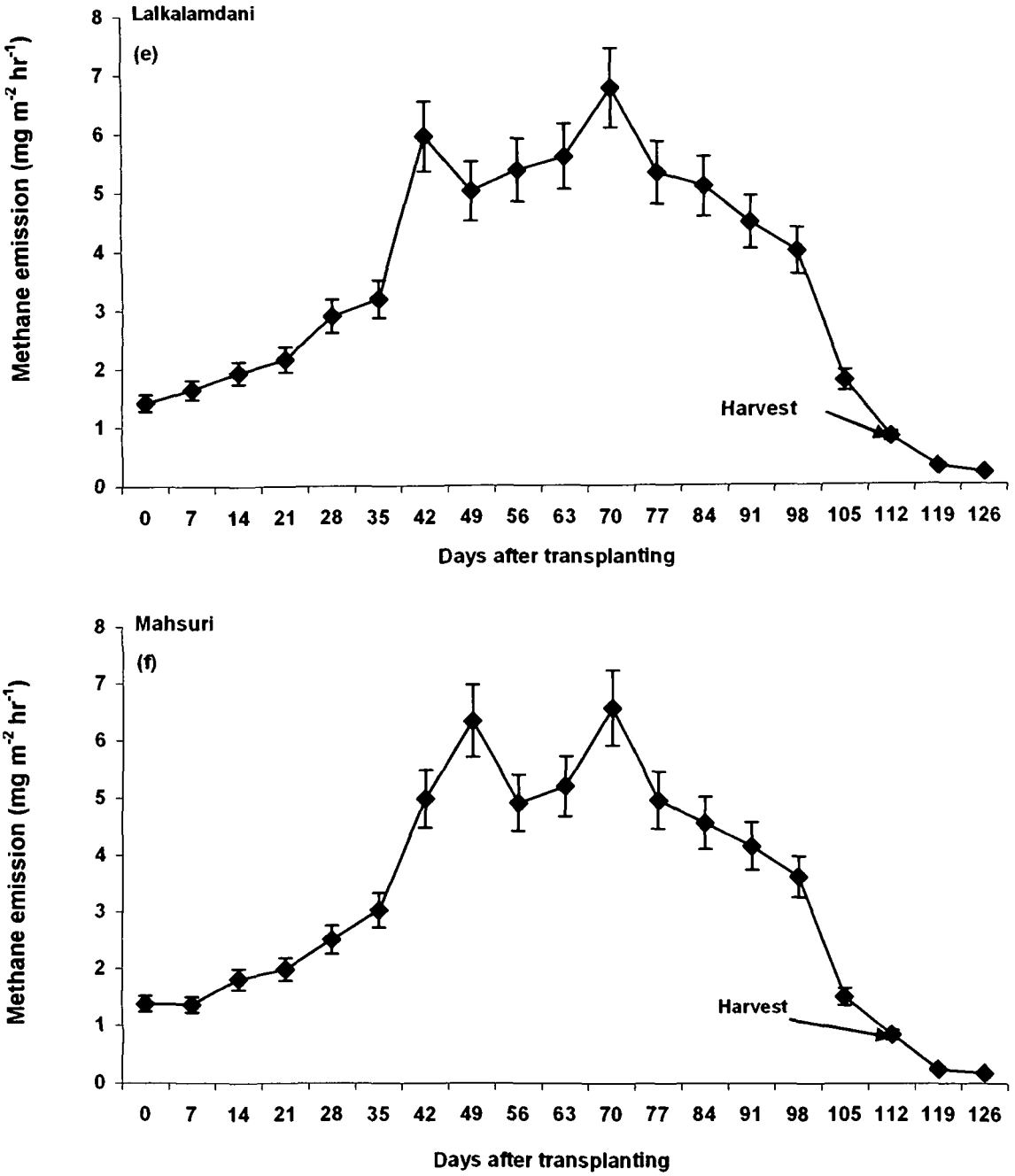


Fig. 4.33. (e) and (f). Methane emission (mg m^{-2} hr^{-1}) from cultivars Lalkalomdani and Mahsuri grown in monsoon / *Sali* ecosystem. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10). When no bars visible, they are completely covered by the marker.

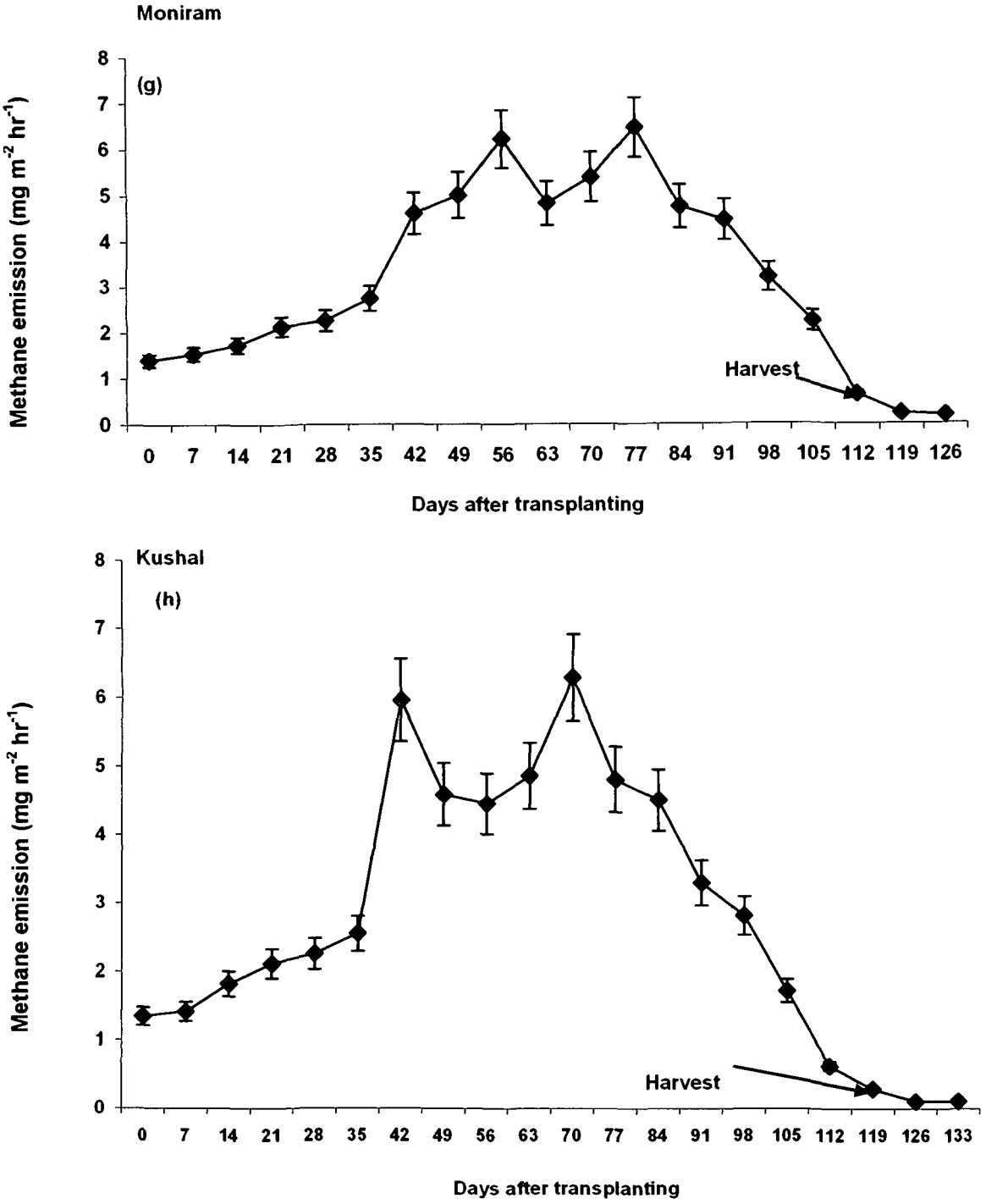


Fig. 4.33. (g) and (h). Methane emission (mg m^{-2} hr^{-1}) from varieties Moniram and Kushal grown in monsoon / *Sali* ecosystem. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10). When no bars visible, they are completely covered by the marker.

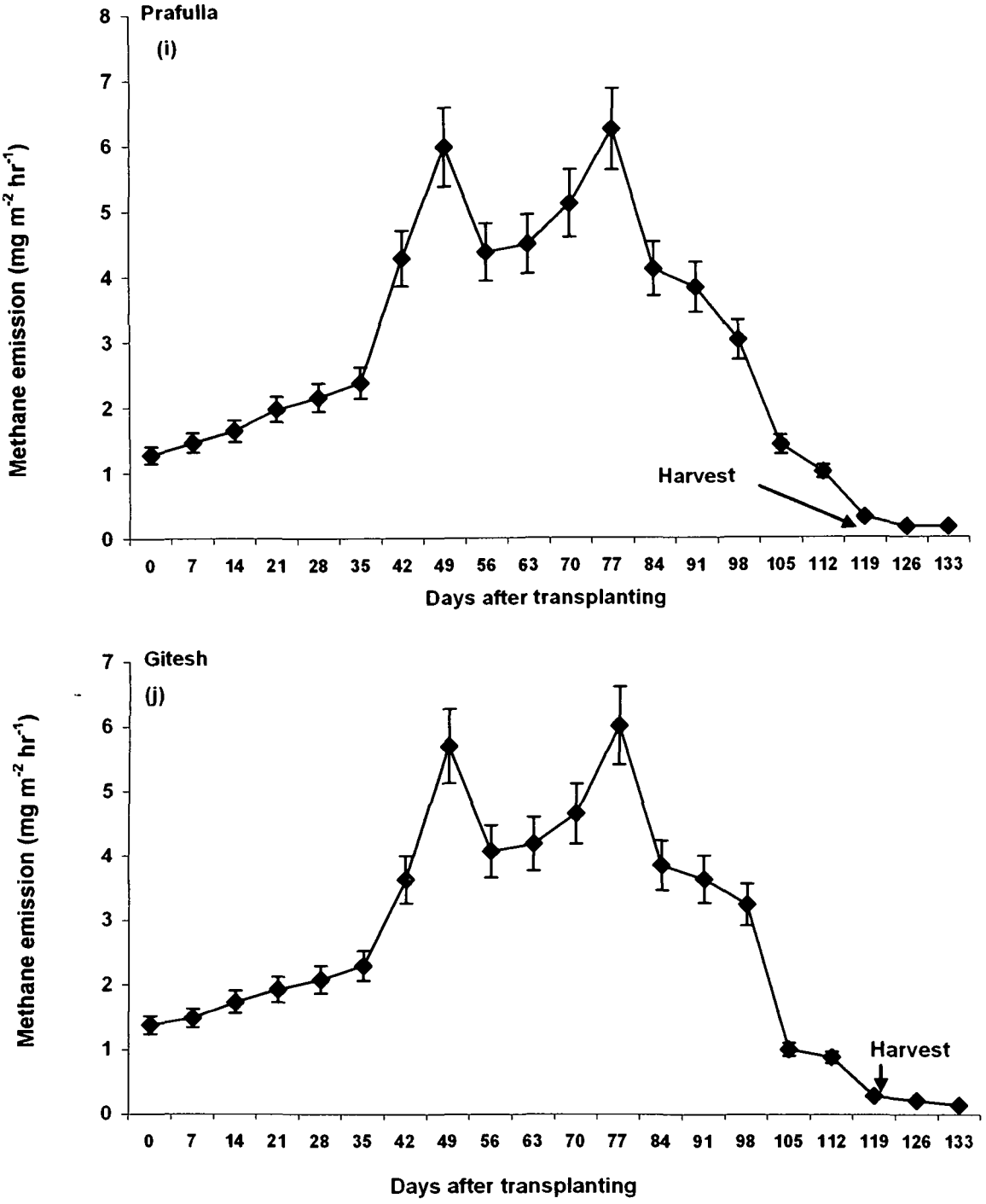


Fig. 4.33. (i) and (j). Methane emission (mg m^{-2} hr^{-1}) from varieties Prafulla and Gitesh grown in monsoon / *Sali* ecosystem. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10). When no bars visible, they are completely covered by the marker.

4.4.5. Soil temperature (°C)

Figure 4.36 represents the soil temperatures (^{0}C) of the experimental fields recorded at weekly interval. Soil temperature of the experimental fields was recorded from the day of transplanting till two weeks after harvest. Higher soil temperature was observed (34.0°C at 7 DAT) during the initial stage of crop growth. With the advancement of growth and development of the crop, the soil temperature decreased gradually up to crop maturation stage.

4.4.6. Plant height (cm)

Plant height (cm) of different rice cultivars was recorded at early tillering stage (28 DAT), active tillering stage (56 DAT), panicle initiation stage (70 DAT), ripening stage (98 DAT) and at harvest of the crop (Fig. 4.37). There was variation in plant height among the cultivars. Rapid increase in plant height was recorded up to ripening stage in all the cultivars. Although there was increase in plant height after the ripening stage, but the increment in height was at a slower rate. Cultivar Rashmisali recorded higher plant height compared to all other cultivars in all the growth stages.

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

Table 4.14 represents the leaf area (cm^2) per hill of the cultivars. Leaf area increased gradually and obtained maximum values at panicle initiation of the crop in all the cultivars. Subsequently, decrease in leaf area per hill was observed towards the maturation of the crop. Basmuthi, Bogajoha, Choimora and Rashmisali recorded higher leaf area per hill compared to other rice cultivars.

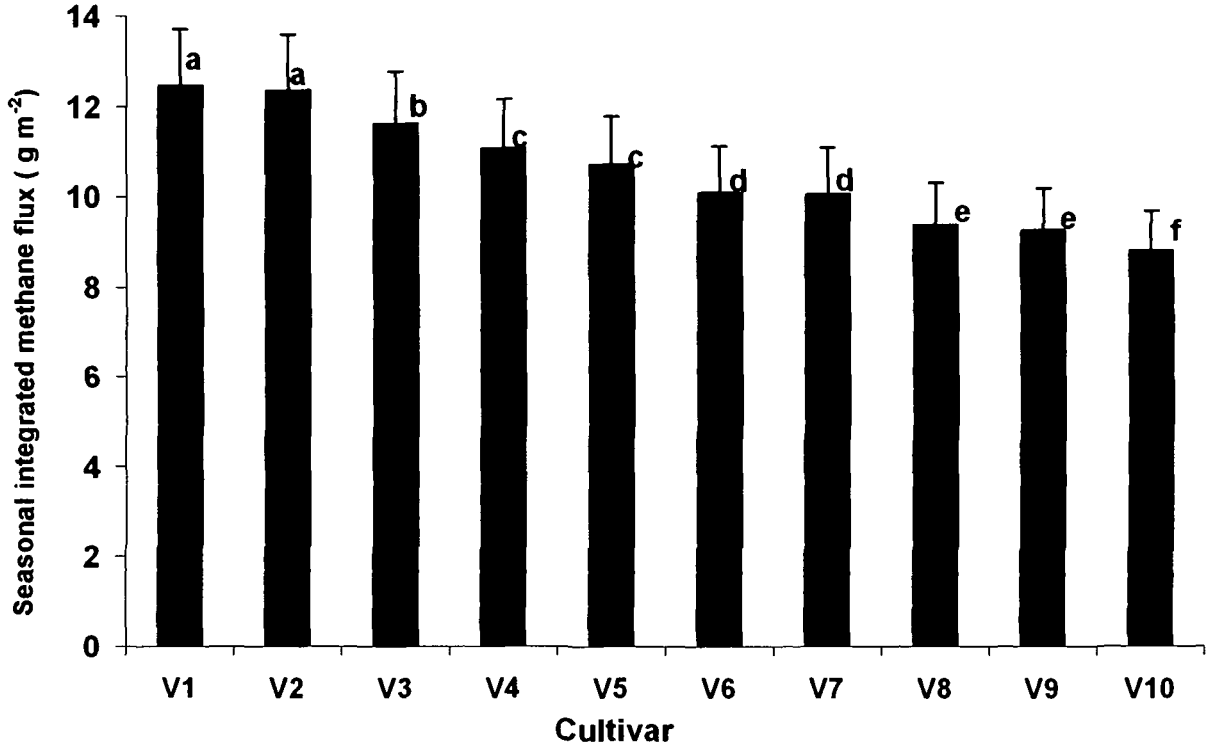


Fig. 4.34. Seasonal integrated methane flux (E_{sif}; g m^{-2}) of ten rice cultivars (bars indicate standard error deviation values multiplied by 10). Bars with similar letter are not significantly different at P < 0.05 level by Duncan's multiple range test.

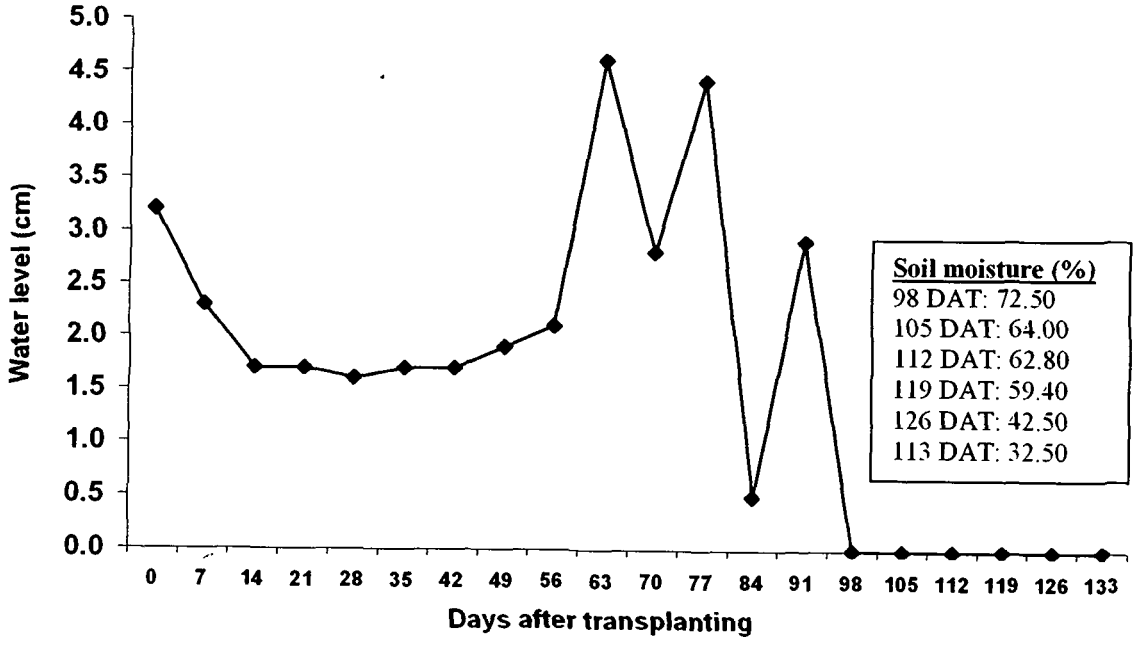


Fig. 4.35. Water level (cm) of the experimental field planted with ten rice cultivars.

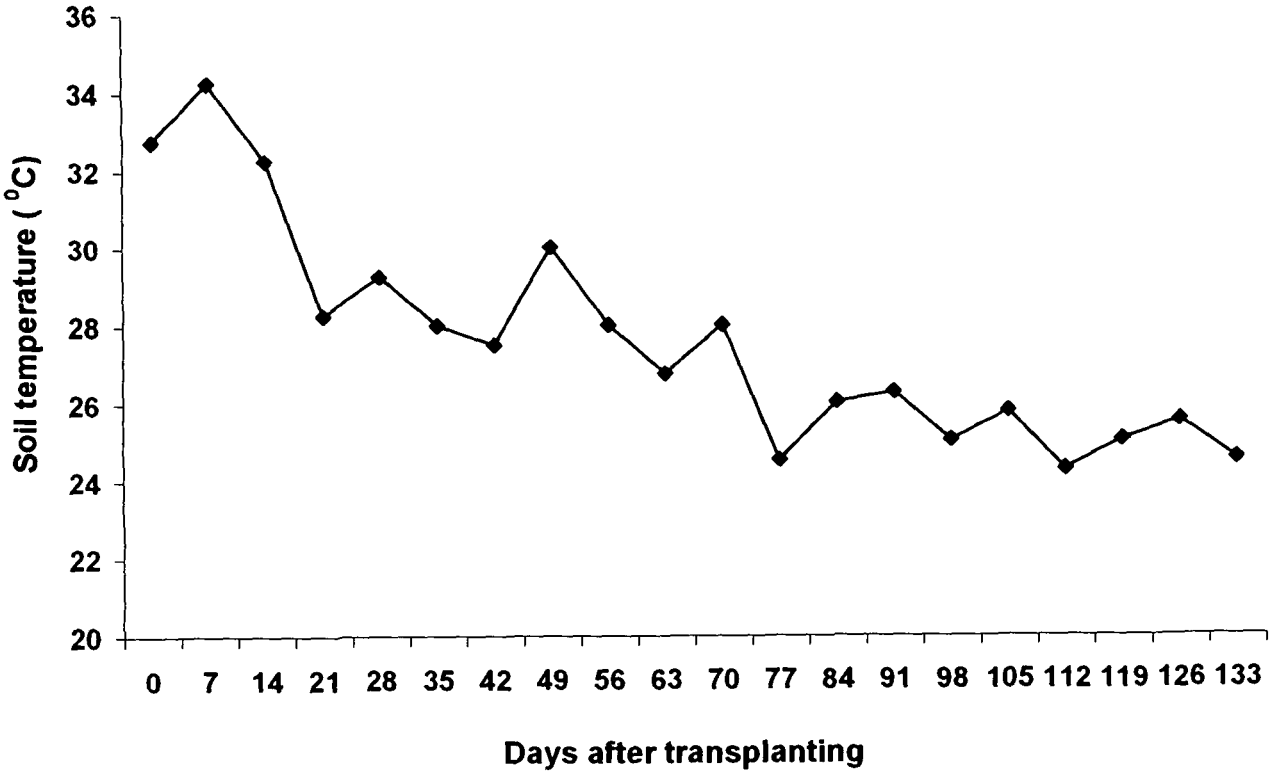


Fig. 4.36. Soil temperature (^{0}C) of the experimental field planted with ten rice cultivars.

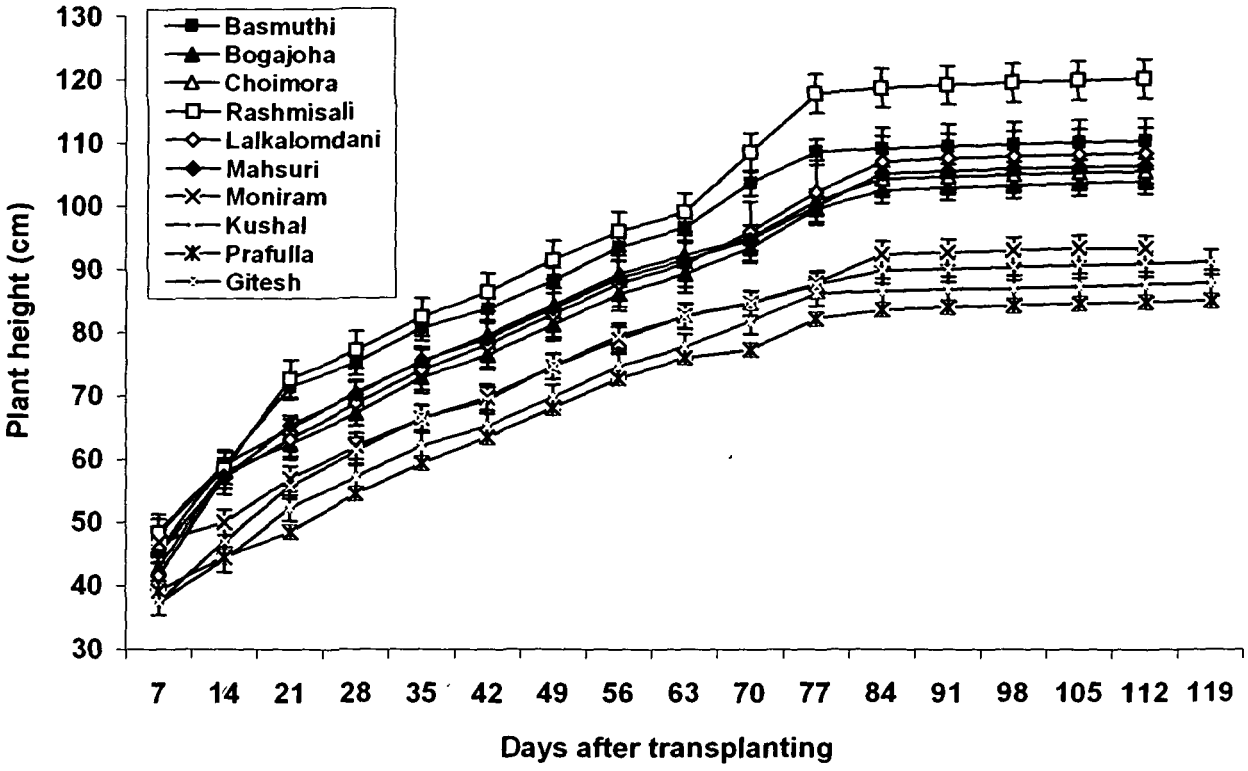


Fig. 4.37. Plant height of ten rice cultivars grown in monsoon / *Sali* ecosystem. Data presented are means ± SEd (vertical bars; SEd values are multiplied by 10). When no bars visible, they are completely covered by the marker.

4.4.8. Leaf area index

Table 4.14 represents the leaf area index of different rice cultivars. In all the cultivars, leaf area index increased gradually and obtained maximum values at panicle initiation of the crop Subsequently, decrease in leaf area index was observed towards the maturation of the crop. Basmuthi, Bogajoha, Choimora and Rashmisali recorded higher leaf area index compared to other rice cultivars.

4.4.9. Tiller number (hill^{-1})

Tiller numbers per hill of the cultivars were recorded at weekly interval and values are presented in Table 4.14. Variation in tiller number was observed among the cultivars. Basmuthi, Bogajoha, Choimora and Rashmisali recorded higher tiller number compared to other rice cultivars. A gradual increase in tiller number was noticed with the advancement of the growth. All the cultivars showed a gradual decrease in tiller number from 63 DAT onwards.

4.4.10. Root length (cm hill^{-1})

Root length (cm) per hill of the cultivars were recorded at weekly interval and presented in Table 4.15. Variation in root length was observed among the cultivars. Basmuthi, Bogajoha, Choimora and Rashmisali recorded higher root length compared to other cultivars. A gradual increase in root length was noticed with the increase in growth of the plant. There was a decline in root length after the ripening stage of the crop.

Table 4.12. Methane flux (mg m^{-2} hr^{-1}) from ten rice cultivars grown in monsoon / *Sali* ecosystem.

	Days after transplanting																	
	0	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119	126
V_1	1 37a	1 61ab	1 95a	3 14a	3 26a	4 68a	5 36d	7 16a	6 19b	6 25b	7 340a	6 46b	5 59b	5 35a	4 37b	3 14a	0 63b	0 28c	0 18c
V_2	1 35a	1 58ab	1 85ab	2 76b	3 12b	4 36b	4 73f	6 27b	6 96a	5 84c	6 080d	7 11a	5 95a	4 98b	4 67a	3 64a	1 71a	0 49a	0 26ab
V_3	1 39a	1 53abcd	1 72bc	2 53c	2 90c	3 85c	6 73a	5 65d	5 74c	5 84c	7 060b	5 93d	5 64b	4 94b	3 96c	2 10bc	1 04b	0 46a	0 21bc
V_4	1 35a	1 57abc	1 63c	2 26d	3 12b	3 49d	6 27b	5 36e	5 53cd	6 98a	5 665e	5 34e	5 19c	4 64c	3 91c	2 12bc	0 78b	0 38b	0 27a
V_5	1 42a	1 64abc	1 93a	2 16de	2 89c	3 18e	5 94c	5 00f	5 35d	5 58d	6 750c	5 30e	5 07c	4 46c	3 97c	1 77bc	0 81b	0 31bc	0 20bc
V_6	1 38a	1 36e	1 81ab	1 98f	2 50d	3 03f	4 98e	6 33b	4 90e	5 19e	6 555c	4 94f	4 55e	4 14d	3 60d	1 50cd	0 83b	0 24c	0 18c
V_7	1 39a	1 54abc	1 73bc	2 13e	2 25e	2 74g	4 59f	5 00f	6 20b	4 81f	5 370f	6 44b	4 73d	4 43c	3 17e	2 22b	0 64b	0 23c	0 18c
V_8	1 34a	1 41cde	1 82bc	2 11e	2 25e	2 54h	5 94c	4 57g	4 44f	4 84f	6 265d	4 79f	4 48e	3 27f	2 79f	1 71bc	0 62b	0 28c	0 10d
V_9	1 28a	1 46de	1 64c	1 97f	2 15ef	2 37i	4 27g	5 96c	4 36f	4 48g	5 095g	6 22c	4 09f	3 81e	3 01ef	1 41cd	1 00b	0 31bc	0 16cd
V_{10}	1 38a	1 49e	1 74bc	1 93f	2 08f	2 29i	3 63h	5 69d	4 06g	4 18h	4 645h	6 00d	3 84g	3 63e	3 23f	1 01d	0 88b	0 28c	0 21bc

In each column, means with the similar letters are not significantly different at P< 0 05 level by DMRT
(V_1 Basmuthi, V_2 Bogajoha, V_3 Choimora, V_4 Rashmisali, V_5 Lalkalomdani, V_6 Mahsuri, V_7 Moniram, V_8 Kushal, V_9 Prafulla, V_{10} Gitesh)

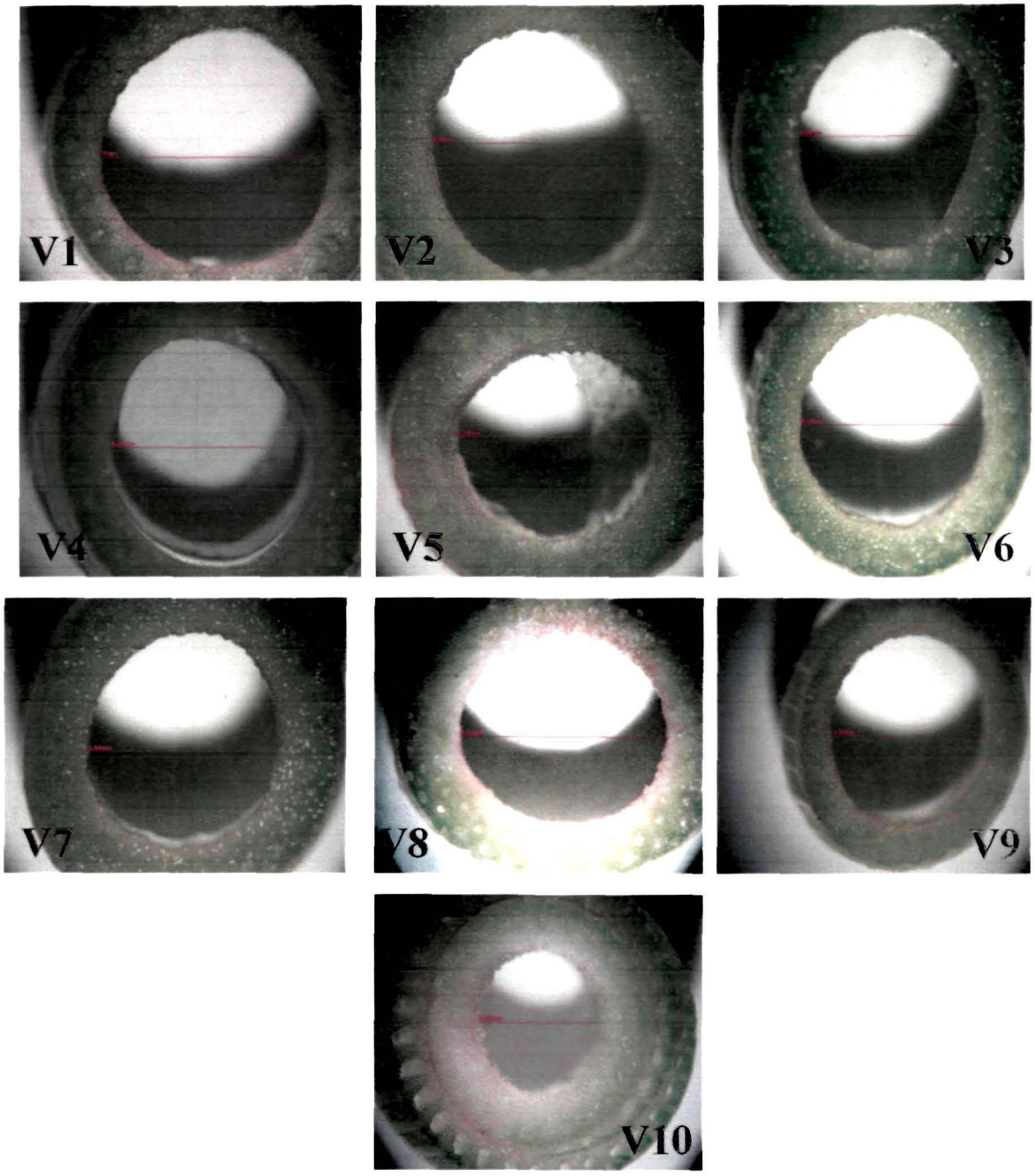


Plate 4.1. Micrographs of medullary cavity of ten *Sali* rice cultivars (Basmuthi (V_1), Bogajoha (V_2), Choimora (V_3), Rashmisali (V_4), Lalkalomdani, (V_5), Mahsuri (V_6), Moniram, (V_7), Kushal, (V_8), Prafulla, (V_9), Gitesh (V_{10}).

4.4.11. Root volume (ml hill^{-1})

Table 4.15 represents the root volume (ml) per hill of the rice cultivars. Variation in root volume was observed among the cultivars. Basmuthi, Bogajoha, Choimora and Rashmisali recorded higher root volume compared to other cultivars. A gradual increase in root volume was noticed with the advancement of the growth of the crop. All the cultivars showed a gradual decrease in root volume after 84 DAT.

4.4.12. Leaf blade dry weight (g hill^{-1})

Table 4.16 represents the leaf blade dry weight (g) per hill of different rice cultivars. Leaf blade dry weight was recorded at early tillering stage (28 DAT), active tillering stage (56 DAT), panicle initiation stage (70 DAT), ripening stage (98DAT) and at harvest of the crop. There was variation in leaf blade dry weight among the cultivars. Rapid increase in leaf blade dry weight was recorded up to the panicle initiation stage in all the cultivars. Cultivar Basmuthi, Bogajoha, Choimora and Rashmisali recorded higher leaf blade dry weight compared to other cultivars.

4.4.13. Leaf sheath dry weight (g hill^{-1})

Table 4.16 represents the leaf sheath dry weight (g) per hill of different rice cultivars. Leaf sheath dry weight was recorded at early tillering stage (28 DAT), active tillering stage (56 DAT), panicle initiation stage (70 DAT), ripening stage (98DAT) and at harvest of the crop. There was variation in leaf sheath dry weight among the cultivars. Rapid increase in leaf sheath dry weight was recorded up to the panicle initiation stage in all the cultivars. Cultivar Basmuthi, Bogajoha, Choimora and Rashmisali recorded higher leaf sheath dry weight compared to other cultivars

Table 4.13. Soil organic carbon (%) the experimental field planted with ten rice cultivars grown in monsoon / *Sali* ecosystem.

	Days after transplanting																
	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119
V_1	0 97a	1 02a	1 04a	1 13a	1 18a	1 36bc	1 41a	1 36b	1 37bc	1 43a	1 42ab	1 40a	1 36ab	1 35a	1 24ab	1 25a	1 21a
V_2	0 97a	0 98a	1 04a	1 07b	1 17ab	1 34c	1 37b	1 41a	1 38b	1 39b	1 43a	1 38ab	1 37a	1 33ab	1 23ab	1 21b	1 21a
V_3	0 96a	0 99a	1 02ab	1 13a	1 16ab	1 39a	1 37b	1 36b	1 37bc	1 41ab	1 40abc	1 36bcd	1 35b	1 31b	1 24ab	1 22b	1 18b
V_4	0 97a	1 01a	1 02ab	1 06bc	1 17ab	1 37ab	1 35b	1 36b	1 40a	1 41b	1 39bcd	1 37bc	1 32c	1 31b	1 24ab	1 19bc	1 20ab
V_5	0 96a	0 99a	1 01ab	1 02de	1 14bc	1 35bc	1 32c	1 33cd	1 38b	1 41b	1 38cde	1 36bc	1 29cd	1 32b	1 25a	1 17cd	1 19ab
V_6	0 97a	0 98a	1 03ab	1 03cd	1 12c	1 19f	1 36b	1 35bc	1 36bc	1 40b	1 38cde	1 33e	1 31c	1 26c	1 19cd	1 21b	1 13cd
V_7	0 96a	0 99a	1 00b	1 04bcd	1 12c	1 29d	1 31c	1 34bc	1 30e	1 36cd	1 37cde	1 33e	1 27de	1 26c	1 21bc	1 15de	1 15c
V_8	0 96a	0 98a	0 99b	1 01de	1 11c	1 34c	1 31c	1 30d	1 36c	1 36c	1 36e	1 35cde	1 30cd	1 26c	1 14e	1 17cd	1 11d
V_9	0 96a	0 99a	0 99b	1 01de	1 07d	1 27de	1 36b	1 34bc	1 32d	1 35cd	1 36de	1 33de	1 26e	1 27c	1 17de	1 14e	1 12d
V_{10}	0 95a	0 98a	0 99b	1 00e	1 01e	1 24e	1 35b	1 32cd	1 31de	1 34d	1 36e	1 33e	1 25e	1 26c	1 20bc	1 15de	1 13cd

In each column, means with the similar letters are not significantly different at $P< 0.05$ level by DMRT.
(V_1: Basmuthi, V_2: Bogajoha, V_3: Choimora, V_4: Rashmisali, V_5: Lalkalomdani, V_6: Mahsuri, V_7: Moniram, V_8: Kushal, V_9: Prafulla, V_{10}: Gitesh)

Table 4.14. Tiller number (hill^{-1}), leaf area (cm^2 hill^{-1}) and leaf area index (LAI) of ten rice cultivars grown in monsoon / *Sali* ecosystem

	Days after transplanting																
	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119
Tiller number																	
V_1	2 33e	5 50b	12 45a	13 48a	14 48a	15 48a	15 70a	15 80a	15 95a	15 73a	15 40a	14 50a	13 35a	12 25a	12 00a	11 60a	
V_2	2 58cde	4 60cd	11 70b	12 73b	13 68b	14 68b	14 78b	14 85b	14 98b	14 85b	14 48b	14 00b	12 98b	11 83b	11 65b	11 38a	
V_3	4 75a	6 83a	10 43d	11 53d	12 53c	13 63c	13 7c	13 80c	13 93c	13 83c	13 45c	12 18c	11 58cd	10 68c	10 50c	10 33bc	
V_4	0 40f	3 35e	9 83e	10 85e	11 08g	12 18f	12 63f	12 78f	12 93f	12 83f	12 50e	11 75d	11 3cd	10 53c	10 35c	10 18bc	
V_5	2 55cde	4 60cd	10 85c	11 78c	12 70c	13 78c	13 90c	14 00c	14 10c	13 98c	13 48c	12 55c	11 6c	10 68c	10 50c	10 38b	
V_6	2 78c	4 83c	9 50fg	10 63ef	11 70de	12 83de	13 00de	13 15de	13 33de	13 23de	12 70e	12 35c	11 28d	10 43c	10 33c	10 10c	
V_7	3 43b	5 43b	9 65ef	10 78e	11 95d	13 03d	13 25d	13 35d	13 55d	13 45d	13 18d	12 40c	11 45cd	10 43c	10 28c	10 18bc	
V_8	2 38de	3 48e	6 70i	7 78h	9 78h	10 95g	11 28g	11 35g	11 63g	11 53g	11 38f	11 25e	10 68e	9 85d	9 65d	9 48d	9 48a
V_9	2 63cd	4 63cd	9 35gh	10 50fg	11 53ef	12 73e	12 85ef	12 95ef	13 13ef	13 00ef	12 58e	11 58de	10 73e	9 78d	9 53d	9 40d	9 40a
V_{10}	2 38de	4 38d	9 20h	10 33g	11 20fg	12 63e	12 83ef	12 93ef	13 15ef	13 05ef	12 53e	11 63de	10 8e	10 00d	9 70d	9 48d	9 45a
Leaf area																	
V_1	45 69a	60 18a	145 38a	346 97a	400 91a	488 97a	646 27a	981 06a	1010 50a	1050 87a	1048 26a	990 41a	829 70b	597 49h	548 42e	528 85b	
V_2	43 87a	58 16ab	143 93a	288 97b	388 58b	448 97b	601 97b	917 97b	965 86b	1043 92a	1030 97b	935 97b	877 97a	650 34c	506 97f	474 97e	
V_3	41 38a	56 40ab	135 91b	255 91c	311 29d	376 30c	540 73c	838 50c	915 50c	980 92b	933 49c	835 90d	755 48g	615 37f	557 46d	532 37b	
V_4	41 25a	55 23ab	134 43b	245 91d	320 69c	350 97d	477 97d	769 89d	971 23b	947 68c	900 85e	864 27c	795 48d	520 91i	415 24g	399 89h	
V_5	40 54ab	53 14bc	133 53b	242 91d	292 97f	381 91c	416 69e	696 95e	845 21d	931 27d	920 74d	809 31e	763 74f	627 84e	577 35bc	440 61g	
V_6	34 36bc	47 93cd	130 37b	195 38e	300 27e	351 36d	398 28g	649 26f	769 59e	865 69e	860 26f	835 89d	805 37c	671 88b	582 47ab	542 89a	
V_7	33 30c	47 74cd	129 73b	173 95f	277 97g	333 18e	405 96f	616 08g	736 30f	847 38f	842 09g	812 97e	776 89e	729 19a	503 98f	449 28f	
V_8	29 93c	43 93d	105 83c	155 07g	253 87h	307 19f	369 27h	573 19h	638 30g	818 63g	813 78h	776 08f	707 16h	605 27g	584 78a	475 08e	427 15c
V_9	27 93c	42 14d	100 91c	125 36h	213 09i	237 97g	336 90i	533 11i	602 12h	781 30h	776 22i	747 12g	682 19i	635 08d	562 12d	485 08d	464 12a
V_{10}	27 32d	41 91d	99 80c	120 69h	154 71j	231 47h	307 96j	489 16j	569 08i	771 23i	751 88j	733 19h	711 08h	595 30h	574 47c	522 18c	435 09b
Leaf area index																	
V_1	0 16a	0 22a	0 52a	1 25a	1 44a	1 76a	2 33a	3 53a	3 64a	3 78a	3 77a	3 57a	2 99b	2 15h	1 97g	1 90c	
V_2	0 16b	0 21b	0 52a	1 04b	1 40b	1 62b	2 17b	3 31b	3 48c	3 76a	3 71b	3 37b	3 16a	2 34c	1 83h	1 71f	
V_3	0 15c	0 20c	0 49b	0 92c	1 12d	1 36d	1 95c	3 02c	3 30d	3 53b	3 36c	3 01d	2 72g	2 22f	2 01f	1 92b	
V_4	0 15c	0 20c	0 48c	0 89d	1 15c	1 26e	1 72d	2 77d	3 50b	3 41c	3 24e	3 11c	2 86d	1 88j	1 50j	1 44i	
V_5	0 15d	0 19d	0 48c	0 87e	1 06f	1 38c	1 50e	2 51e	3 04e	3 36d	3 32d	2 91f	2 75f	2 26e	2 08c	1 59h	
V_6	0 12e	0 17e	0 47d	0 70f	1 08e	1 27e	1 43g	2 34f	2 77f	3 12e	3 10f	3 01d	2 90c	2 42b	2 10b	1 95a	
V_7	0 12e	0 17e	0 47e	0 63g	1 00g	1 20f	1 46f	2 22g	2 65g	3 05f	3 03g	2 93e	2 80e	2 63a	1 81i	1 62g	
V_8	0 11f	0 16f	0 38f	0 56h	0 91h	1 11g	1 33h	2 06h	2 30h	2 95g	2 93h	2 79g	2 55i	2 18g	2 11a	1 71f	1 54c
V_9	0 10g	0 15g	0 36g	0 45i	0 77i	0 86h	1 21i	1 92i	2 17i	2 81h	2 79i	2 69h	2 46j	2 29d	2 02e	1 75e	1 67a
V_{10}	0 10g	0 15g	0 36g	0 43j	0 56j	0 83i	1 11j	1 76j	2 05j	2 78i	2 71j	2 64i	2 56h	2 14i	2 07d	1 88d	1 57b

In each column, means with the similar letters are not significantly different at P< 0 05 level by DMRT

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

4.4.14. Culm dry weight (g hill^{-1})

Table 4.16 represents the culm dry weight (g) per hill of different cultivars. Culm dry weight was recorded at early tillering stage (28 DAT), active tillering stage (56 DAT), panicle initiation stage (70 DAT), ripening stage (98DAT) and at harvest of the crop. There was variation in culm dry weight among the cultivars. Rapid increase in culm dry weight was recorded up to the ripening stage in all the cultivars. Although there was increase in culm dry weight after the ripening stage, but the increment in dry weight was at a slower rate. Cultivar Basmuthi, Bogajoha, Choimora and Rashmisali recorded higher culm dry weight compared to other cultivars.

4.4.15. Shoot dry weight (g hill^{-1})

Shoot dry weight (g) per hill of the cultivars were recorded at weekly interval and presented in Table 4.17. Variation in shoot dry weight was observed among the cultivars. Basmuthi, Bogajoha, Choimora and Rashmisali recorded higher shoot dry weight compared to other rice cultivars. A gradual increase in shoot dry weight was noticed with the advancement of growth and development of the crop. Dry weight was highest at 63 DAT and thereafter the cultivars showed decline in shoot dry weight.

4.4.16. Root dry weight (g hill^{-1})

Root dry weight (g) per hill of the cultivars was recorded at weekly interval and values are presented in Table 4.17. There was variation in root dry weight among the cultivars. Basmuthi, Bogajoha, Choimora and Rashmisali recorded higher root dry weight compared to other rice cultivars. A gradual increase in root dry weight was noticed with the advancement of growth and development of the crop. The cultivars showed a gradual decrease in root dry weight after panicle initiation and ripening stage.

Table 4.15. Root volume (ml hill^{-1}) and total root length (cm hill^{-1}) of ten rice cultivars grown in monsoon / *Sali* ecosystem.

	Days after transplanting																
	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119
Root volume																	
V_1	1 90a	4 00a	5 80a	6 10a	13 00a	17 00b	24 80a	26 40a	32 70a	34 50a	34 90b	34 90b	26 40a	24 50a	22 10a	18 80a	
V_2	1 90a	3 60b	5 40b	5 70b	11 20b	17 50a	23 10b	26 40a	31 00b	34 50a	35 70a	36 00a	25 60b	22 40b	21 30b	16 50c	
V_3	1 90a	3 60b	5 40b	5 80b	10 40c	13 20c	17 40c	20 40b	22 00d	29 10b	31 00c	32 00c	21 00f	19 70d	19 00d	15 50e	
V_4	1 80a	2 40c	4 00d	5 00c	10 30c	12 40d	15 00d	19 30c	24 20c	26 30d	29 70d	30 50d	22 90c	19 30e	19 10d	17 10b	
V_5	1 80a	2 30c	4 30c	4 60d	8 70d	11 70e	14 30e	16 90d	20 40e	27 00c	27 90e	30 40d	22 70d	21 50c	20 30c	15 30f	
V_6	2 00a	2 30c	3 50e	4 10e	7 20e	9 30f	13 50f	14 90e	17 90g	25 40e	26 10f	29 30e	22 00e	19 50e	19 20d	13 80h	
V_7	1 90a	2 30c	3 30e	3 70f	6 70f	8 70h	12 80g	13 90f	18 80f	24 90f	25 40g	28 50f	21 10f	18 80f	18 40e	15 70d	
V_8	1 80a	2 20c	3 30e	4 10e	6 00g	9 00g	12 00h	13 50g	17 20h	24 20g	24 70h	26 90g	20 30g	18 00g	16 90f	15 10g	12 00a
V_9	1 90a	2 20c	3 30e	3 40g	5 50h	7 30i	11 30i	13 00h	15 00i	21 60h	24 00i	25 70h	19 70h	16 80h	16 40g	13 50i	9 50c
V_{10}	1 90a	2 20c	2 60f	2 90h	5 40h	6 50j	10 10j	10 80i	14 10j	20 20i	21 30j	24 50i	19 20i	16 30i	15 60h	12 60j	11 40b
Root length																	
V_1	136 31a	305 65a	322 64a	471 89a	1001 41a	1211 38b	1651 27a	2031 17a	2221 36a	2301 86a	2491 92a	2323 63b	2202 36a	2040 26a	1697 25b	1566 55a	
V_2	134 24a	278 62b	300 81b	408 34b	861 27b	1251 30a	1541 93b	2031 87a	2131 17b	2301 86a	2361 89b	2401 14a	2134 29b	1869 45b	1781 11a	1378 49c	
V_3	135 19a	279 56b	301 75b	409 29b	801 17c	941 93c	1161 49c	1571 16b	1831 81d	2071 10b	2211 19c	2131 28c	1751 36f	1641 38d	1541 36d	1291 83e	
V_4	131 75a	181 71c	221 14e	386 00c	789 28c	884 09d	1001 89d	1481 07c	1881 16c	2001 26c	2119 40d	2031 09d	1911 59c	1611 86e	1481 79e	1421 52b	
V_5	127 96a	177 65c	258 84c	357 95d	666 63d	835 52e	956 44e	1301 62d	1696 52e	1801 47d	1995 55e	2024 59d	1892 43d	1788 59c	1565 29c	1274 63f	
V_6	139 54a	174 67c	195 64f	318 07e	553 21e	667 10f	898 72f	1050 20f	1490 11g	1696 06e	1864 14f	1950 17e	1836 02e	1621 18e	1479 88e	1153 22h	
V_7	136 95a	173 99c	242 89d	285 83f	516 44f	620 33h	853 25g	1070 36e	1565 33f	1658 28f	1817 36g	1902 40f	1761 24f	1565 40f	1415 10f	1312 44d	
V_8	128 71a	171 49c	185 71fg	314 47e	458 60g	643 61g	801 42h	1038 21f	1434 50h	1612 45g	1761 53h	1790 56g	1694 41g	1499 57g	1301 27g	1259 61g	1001 61a
V_9	135 77a	172 45c	183 64fg	259 79g	421 13h	520 44i	755 86i	886 29g	1253 02i	1441 97h	1598 05i	1711 09h	1639 07h	1402 09h	1259 79h	1122 13i	789 13c
V_{10}	134 13a	170 46c	180 14g	224 85h	411 69h	462 86j	733 58j	834 56h	1177 50j	1349 45i	1521 53j	1630 56i	1600 90i	1356 57i	1201 27i	1046 61j	952 61b

In each column, means with the similar letters are not significantly different at $P< 0.05$ level by DMRT.

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

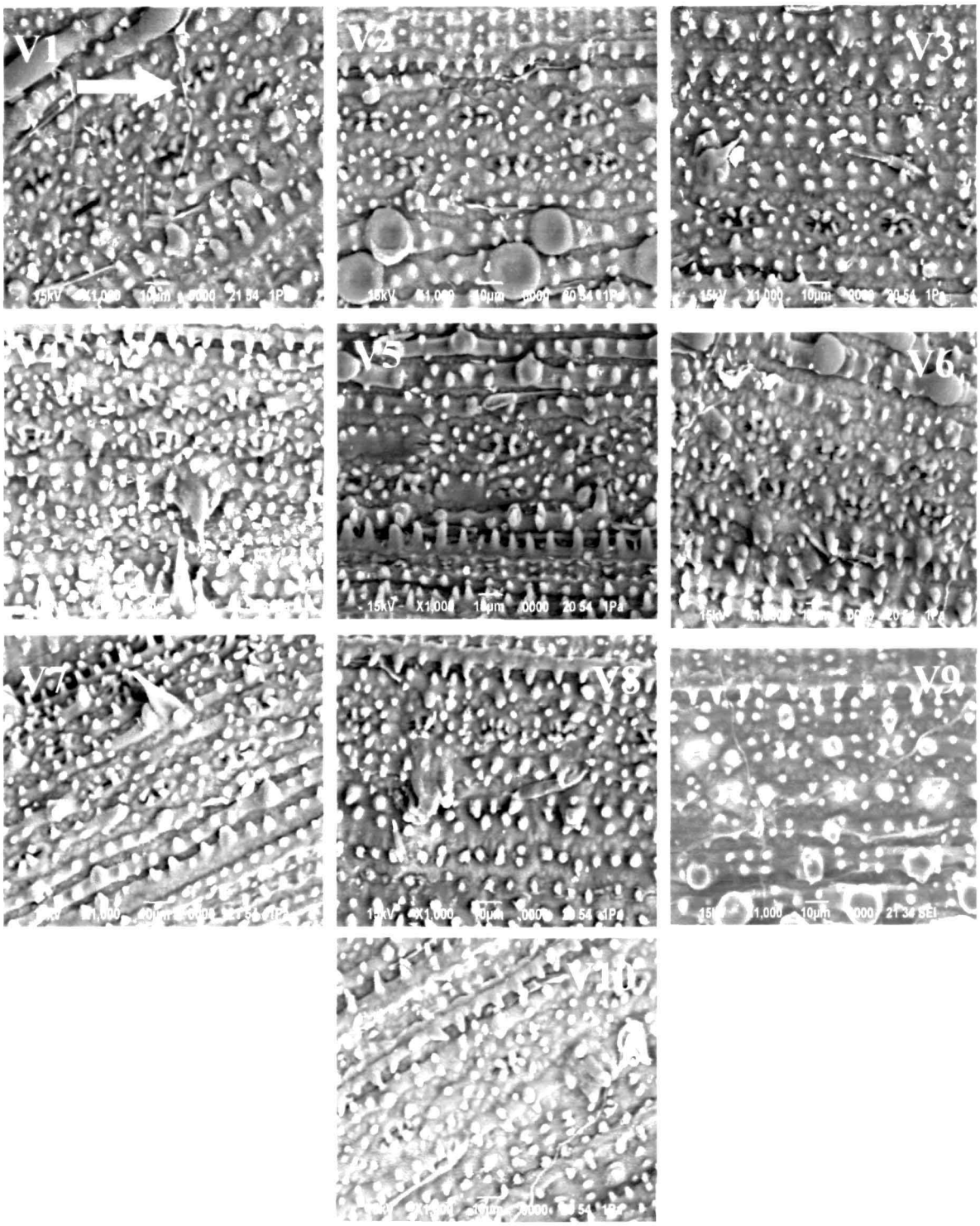


Plate 4.2. Scanning electron micrographs of stomata on the adaxial leaf surfaces of ten *Sali* rice cultivars [Basmuthi (V_1), Bogajoha (V_2), Choimora (V_3), Rashmisali (V_4), Lalkalomdani (V_5), Mahsuri (V_6), Moniram (V_7), Kushal (V_8), Prafulla (V_9), Gitesh (V_{10})]. Arrows point to the stomata.

4.4.17. Leaf photosynthetic rate (μ mol CO_2 m^{-2} sec^{-1})

Leaf photosynthetic rates (μ mol CO_2 m^{-2} sec^{-1}) of the cultivars were recorded at weekly interval and data are presented in Table 4.18. During the vegetative growth phase, higher photosynthetic rate was recorded in high CH_4 emitting cultivars *viz.* Basmuthi, Bogajoha and Choimora compared to low emitting cultivars *viz.* Prafulla, Kushal and Gitesh. During the reproductive stage, the trend was found to be reversed as higher photosynthetic rate was recorded in low CH_4 emitting cultivars. Lower rate of photosynthesis was recorded in cultivars Basmuthi, Bogajoha and Choimora (higher CH_4 emitting cultivars) during the reproductive stage.

4.4.18. Dry weight of developing panicle (g $hill^{-1}$)

After panicle initiation, dry weights (g) of developing panicles of different cultivars were recorded at 7 days interval till harvest and the data are presented in Table 4.19. Panicle dry weight increased gradually and was maximum at harvest in all the cultivars. Higher panicle dry weight was recorded in cultivars Prafulla, Kushal and Gitesh compared to Basmuthi, Bogajoha, Choimora and Rashmisali.

4.4.19. Size of the medullary cavity (mm)

Significant differences in the size of the medullary cavity among cultivars were observed (Table 4.20; Plate 4.1). High methane emitting cultivars *viz.* Basmuthi and Bogajoha recorded greater size of medullary cavity (6.93mm and 7.21mm in diameter, respectively) than lower methane emitting cultivars Gitesh and Prafulla (3.92 mm and 5.41mm). Significant positive correlation was recorded between methane emission and size of medullary cavity (Table 4.22).

Table 4.16. Dry weight (g hill^{-1}) of plant parts (culm, leaf blade and leaf sheath) of ten rice cultivars grown in monsoon / *Sali* ecosystem.

	Days after transplanting																
	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119
Culm dry weight																	
V_1	0.37a	0.77a	0.94b	1.19b	1.99b	2.08b	5.71b	8.21b	11.84b	12.91b	15.15b	15.56b	16.51b	18.57b	19.72b	19.77b	
V_2	0.31e	0.75a	0.84e	1.09e	1.83e	1.92f	5.33f	7.67f	11.10e	11.83e	13.88e	14.48f	15.36e	17.28f	18.38c	18.41f	
V_3	0.34d	0.76a	0.86d	1.13c	1.87c	1.98c	5.46c	7.82c	11.34c	11.86d	14.05d	14.76d	15.65d	17.60d	18.7d	18.76d	
V_4	0.36b	0.76b	0.96a	1.22a	2.02a	2.13a	5.86a	8.35a	12.03a	13.42a	16.28a	16.75a	17.79a	19.99a	21.25a	21.32a	
V_5	0.31e	0.75c	0.84e	1.10d	1.83d	1.93e	5.35e	7.68e	11.08f	11.91c	14.08c	15.14c	16.05c	18.05c	19.17cd	19.23c	
V_6	0.34d	0.74d	0.88c	1.13c	1.87c	1.97d	5.42d	7.78d	11.11d	11.75f	13.74f	14.72e	15.61f	17.55e	18.63c	18.69e	
V_7	0.35c	0.65e	0.76f	0.98f	1.63g	1.74g	4.85g	7.00g	10.18g	10.64g	12.24h	13.08g	13.85g	15.58h	16.3e	16.43g	
V_8	0.28g	0.57h	0.7h	0.91f	1.53h	1.61i	4.52i	6.56i	9.52i	10.15i	11.94i	12.24i	12.96i	14.59i	15.51f	15.56i	15.59b
V_9	0.3f	0.58g	0.65i	0.86h	1.47i	1.57j	4.40j	6.37j	9.31j	9.63j	11.33j	11.76j	12.55j	14.12j	15.01g	15.06j	15.09c
V_{10}	0.28g	0.61f	0.75g	0.98f	1.64f	1.72h	4.84h	6.99h	10.12h	10.58h	12.26g	12.81h	13.56h	15.23g	16.19e	16.26h	16.29a
Leaf blade dry weight																	
V_1	0.25a	0.29a	0.61a	1.71a	2.74a	3.68a	5.55a	9.72a	11.13a	14.41a	13.64a	11.89a	9.97c	7.96e	7.14f	7.04d	
V_2	0.24ab	0.28b	0.61a	1.42b	2.65b	3.38b	5.17b	9.10b	10.63b	13.84b	13.41b	11.24b	10.55a	8.66c	6.59h	6.28i	
V_3	0.23bc	0.27c	0.58b	1.30c	2.26c	2.97c	4.47c	8.50c	9.88c	12.92c	12.46c	10.34d	9.44e	8.31d	7.97b	7.78b	
V_4	0.23bc	0.27c	0.57bc	1.21d	2.19d	2.72e	4.1d	7.63d	9.69d	12.05d	11.72e	10.38c	9.98b	6.94j	6.41i	6.02j	
V_5	0.22c	0.26d	0.56cd	1.20e	2e	2.87d	3.57e	6.91e	9.31e	11.61e	11.98d	9.72f	9.17g	7.73h	7.52c	6.63h	
V_6	0.19d	0.23e	0.55d	0.97f	2.05f	2.65f	3.42g	6.44f	8.48f	10.62f	11.02f	10.04e	9.67d	8.95a	8.58a	8.16a	
V_7	0.18d	0.22e	0.55d	0.86g	1.9g	2.51g	3.48f	6.11g	7.9g	10.14g	10.58g	9.64g	9.33f	8.81b	6.94g	6.66f	
V_8	0.16e	0.2f	0.45e	0.77h	1.74h	2.31h	3.17h	5.68h	6.85h	9.56h	10.32h	9.01h	8.5h	7.80f	7.36d	7.15h	6.21a
V_9	0.15e	0.19g	0.43f	0.62i	1.46i	1.79i	2.89i	5.29i	6.46i	9.11i	9.54i	8.66i	8.14j	7.75g	6.93g	6.65i	6.17a
V_{10}	0.15e	0.19g	0.42f	0.60j	1.06j	1.75j	2.64j	4.85j	6.27j	8.62j	9.11j	8.59j	8.2i	7.51i	7.17e	6.82j	5.49b
Leaf sheath dry weight																	
V_1	0.23a	0.25a	0.57a	1.61a	2.38a	3.51a	5.41a	8.48a	10.98a	14.62a	13.84a	12.16a	10.24bc	7.88c	7.25b	7.17b	
V_2	0.23a	0.23b	0.57a	1.35b	2.28b	3.21b	4.76b	7.84b	10.05b	14.22b	13.78a	11.66b	11.1a	8.31b	6.74c	6.60d	
V_3	0.21b	0.23b	0.54b	1.22c	1.96c	2.83c	4.36c	7.42c	9.75c	13.11c	12.64b	10.57cd	9.7d	8.22b	8.02a	7.32ab	
V_4	0.21b	0.21c	0.53bc	1.15d	1.88d	2.59d	3.78d	6.58d	9.15d	12.38d	12.04c	10.77c	10.5b	6.66f	6.23e	5.42g	
V_5	0.2c	0.22c	0.52bcd	1.13e	1.74e	2.74c	3.48e	6.03e	9.19d	11.78e	12.15c	9.94e	9.42d	7.65d	7.28b	6.06f	
V_6	0.18d	0.19d	0.51cd	0.92f	1.77e	2.52d	3.15f	5.55f	8e	10.91f	11.32d	10.42d	10.18c	8.58a	8.12a	7.38a	
V_7	0.17e	0.19d	0.51d	0.81g	1.65f	2.39e	3.39e	5.33g	7.8e	10.29g	10.73e	9.86e	9.59d	8.72a	7.04b	6.82c	
V_8	0.16f	0.17e	0.42e	0.73h	1.49g	2.2f	2.92g	4.90h	6.47f	9.82h	10.6e	9.35f	8.94e	7.48d	6.35de	6.15ef	5.54b
V_9	0.14g	0.17e	0.39f	0.58i	1.27h	1.71g	2.81h	4.61i	6.37f	9.24i	9.68f	8.86g	8.36g	7.67d	7.03b	6.81c	6.03a
V_{10}	0.14g	0.16f	0.39f	0.57i	0.91i	1.66g	2.43i	4.18j	5.92g	8.86j	9.36g	8.91g	8.63f	7.21e	6.58e	6.27e	5.11c

In each column, means with the similar letters are not significantly different at $P< 0.05$ level by DMRT.

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

Table 4.17. Root and shoot dry weight (g hill^{-1}) of ten rice cultivars grown in monsoon / *Sali* ecosystem

	Days after transplanting																
	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119
Root dry weight																	
V_1	0 06a	0 13a	0 23a	0 37a	0 70a	1 11a	1 91a	2 85a	3 57a	4 04a	4 61a	4 45a	3 90a	3 65a	2 50d	2 37b	
V_2	0 06a	0 12b	0 21a	0 29b	0 42b	1 03b	1 48b	2 77b	3 21b	3 96b	4 25b	4 59b	3 81b	3 19b	2 71a	2 23d	
V_3	0 05a	0 09c	0 17bc	0 21c	0 37d	0 72d	1 25c	1 58c	2 47d	3 38c	3 88c	4 07c	3 20h	2 69g	2 58c	2 12f	
V_4	0 05a	0 08d	0 15cd	0 18d	0 39c	0 77c	1 02d	1 42d	2 57c	3 24d	3 79d	3 95d	3 57d	2 57h	2 43e	2 29c	
V_5	0 05a	0 08d	0 18b	0 17de	0 36d	0 67e	0 91f	1 33e	2 29e	2 83e	3 48e	3 65e	3 62c	2 79e	2 63b	2 42a	
V_6	0 05a	0 08d	0 14de	0 15ef	0 28f	0 60g	0 86g	1 13f	2 11f	2 68f	3 30f	3 42g	3 33f	2 45i	2 29g	2 22d	
V_7	0 05a	0 08d	0 17bc	0 14f	0 33e	0 63f	0 96e	1 08g	1 83g	2 54g	3 27g	3 55f	3 25g	2 76f	2 18h	2 09g	
V_8	0 05a	0 08d	0 13de	0 15ef	0 28f	0 56h	0 77h	1 05h	1 69h	2 45h	3 03h	3 44g	3 41e	3 03c	2 35f	2 16e	2 03a
V_9	0 05a	0 08d	0 13ef	0 12f	0 23g	0 45i	0 77h	0 89i	1 48i	2 24i	2 93i	3 25h	3 25g	2 87d	1 99j	1 72i	1 67b
V_{10}	0 05a	0 08d	0 13f	0 11f	0 21h	0 40j	0 75i	0 84j	1 38j	2 07j	2 84j	3 21i	3 08i	2 57h	2 08i	1 81h	1 60c
Shoot dry weight																	
V_1	0.85a	1.30a	2.11a	4.51a	7.11a	9.27a	16.67a	26.40a	33.94a	41.94a	42.62a	39.61a	36.72c	34.40b	34.10b	33.97b	
V_2	0.78c	1.25b	2.01c	3.85b	6.75b	8.51b	15.26b	24.62b	31.77b	39.89b	41.06b	37.38c	37.01b	34.24bc	31.70d	31.29e	
V_3	0.78c	1.26b	1.97d	3.65c	6.09c	7.78c	14.29c	23.73c	30.96c	37.89c	39.15d	35.67d	34.79e	34.13c	34.04b	33.86b	
V_4	0.80b	1.24c	2.05b	3.58d	6.10c	7.44e	13.74d	22.56d	30.87c	37.84c	40.03c	37.90b	37.6a	33.59d	33.30c	32.76c	
V_5	0.74d	1.22d	1.91f	3.42e	5.57e	7.54d	12.4e	20.62e	29.57d	35.30d	38.21e	34.80f	34.65e	33.43d	33.00c	31.92d	
V_6	0.71e	1.15e	1.93e	3.02f	5.68d	7.13f	11.99f	19.76f	27.59e	33.28e	36.07f	35.17e	35.08d	35.08a	35.00a	34.23a	
V_7	0.70f	1.06f	1.81g	2.64g	5.18f	6.64g	11.73g	18.43g	25.87f	31.07f	33.55g	32.89g	32.77f	32.50e	30.29e	29.91f	
V_8	0.59g	0.94h	1.56h	2.40h	4.76g	6.12h	10.61h	17.14h	22.83g	29.53g	32.85h	30.60h	30.40g	29.88f	29.21f	28.86h	27.33a
V_9	0.59g	0.94h	1.47i	2.06j	4.19h	5.07i	10.10i	16.28i	22.14h	27.98h	30.54i	29.27i	29.04h	29.00g	28.97f	28.51i	27.28a
V_{10}	0.57h	0.96g	1.56h	2.14i	3.61i	5.13i	9.91j	16.02j	22.31h	28.05h	30.72i	30.55h	30.39g	29.95f	29.94e	29.35g	26.89b

In each column, means with the similar letters are not significantly different at $P< 0.05$ level by DMRT.

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

Table 4.18. Photosynthetic (μ mol CO_2 m^{-2} sec^{-1}) and transpirational (m mol H_2O m^{-2} sec^{-1}) rate of ten rice cultivars grown in monsoon / *Sali* ecosystem.

	Days after transplanting															
	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119
Photosynthetic rate																	
V_1	33.04a	14.75a	26.25a	22.63b	17.82a	23.07b	14.85a	29.98b	22.10b	24.32a	21.58de	13.65f	12.70h	9.45g	6.74f	4.21h	
V_2	19.95b	14.80a	23.07b	25.80a	14.37b	26.25a	11.87b	34.87a	24.90a	23.11b	20.87ef	13.50f	9.44i	10.95f	6.94f	5.92g	
V_3	12.18c	12.90b	17.00c	18.38c	14.19b	21.36c	11.13c	29.25b	21.97b	22.48c	21.53de	14.60e	13.2g0	11.90e	6.84f	6.16g	
V_4	7.24de	12.00c	13.48d	16.16e	13.79c	20.73d	8.56d	18.24d	20.80c	21.26d	25.10b	16.33d	16.15e	15.43d	10.00d	7.30f	
V_5	8.43d	11.54d	11.62e	17.43d	13.45c	19.68e	7.55e	26.05c	19.97d	21.93c	29.44a	14.83e	16.30e	15.38d	7.16f	7.66e	
V_6	7.19de	9.52e	11.11e	11.75f	11.22d	19.44e	7.11ef	16.38de	18.89e	17.80f	22.63cd	16.05d	13.58f	15.45d	9.50e	7.81e	
V_7	6.94de	9.39e	10.20f	16.10e	10.87d	7.82g	6.98ef	18.14d	17.47f	19.12e	23.78bc	16.85c	19.83c	15.73d	10.98c	14.70d	
V_8	6.26e	7.28f	8.19g	11.68f	9.87e	10.20f	6.46f	15.82e	14.86g	17.32fg	15.98g	16.98c	16.73d	17.83c	10.26d	15.94c	4.29c
V_9	2.44f	4.73g	7.82g	8.01g	9.81e	3.88i	5.73g	14.39e	14.60g	17.00g	19.85f	19.35b	20.95b	20.85a	12.14b	16.39b	5.89b
V_{10}	5.60e	4.69g	4.76h	7.08h	8.54f	4.75h	5.36g	9.87f	11.01h	11.11h	16.65g	22.80a	23.10a	18.58b	13.80a	16.84a	6.62a
Transpirational rate																	
V_1	18 35a	6 93b	6 62c	12 33a	5 20a	5 20b	4 44a	5 51c	9 03e	13 73b	5 73c	3 15e	2 36e	1 84a	0 67e	0 38a	
V_2	13 86b	6 88b	5 21d	11 88b	4 26e	6 62a	4 01b	11 65a	13 50b	13 65b	5 77c	2 80f	1 29f	0 79b	0 61e	0 27a	
V_3	7 06e	8 34a	8 66a	8 58c	4 50c	4 08c	4 39a	8 64b	8 43f	12 26c	5 07d	4 28c	1 24f	0 68b	1 03d	0 68b	
V_4	6 23f	5 91c	7 44b	7 06e	4 32d	2 54e	1 66d	4 58d	18 03a	10 88d	6 23b	3 84d	3 48c	0 61bc	0 38cd	0 87bc	
V_5	10 19c	3 30i	6 77c	6 99e	4 70b	2 17ef	0 51f	8 06b	12 09c	14 43a	5 75c	2 16g	3 90b	0 20c	1 03cd	0 83bc	
V_6	9 79d	5 15d	6 46c	4 49f	3 54g	3 17d	0 56f	5 58c	9 19e	10 09e	4 52e	3 17e	0 55g	0 73b	0 55c	0 97c	
V_7	6 24f	4 86e	2 00e	7 72d	3 89f	1 50g	2 80c	3 96e	10 84d	11 16d	6 63a	3 69d	2 74d	1 97a	0 44b	1 32d	
V_8	9 76d	3 92h	5 45c	3 73g	2 80i	2 00f	1 37de	4 68d	4 37g	7 93g	3 53f	3 61d	2 68d	1 86a	0 99cd	0 84bc	1 97b
V_9	4 65g	4 23g	1 51f	3 43g	2 70j	1 00h	1 24e	3 64e	9 17e	9 43f	5 56c	4 73b	5 38a	2 24a	1 05a	1 76e	0 78a
V_{10}	7 12e	4 35f	0 41g	3 02h	3 00h	0 44i	1 27e	4 96cd	3 36h	12 31c	4 36e	6 34a	3 57c	0 86b	0 90b	1 27d	1 92b

In each column, means with the similar letters are not significantly different at P< 0.05 level by DMRT.
(V_1: Basmuthi, V_2: Bogajoha, V_3: Choimora, V_4: Rashmisali, V_5: Lalkalomdani, V_6: Mahsuri, V_7: Moniram, V_8: Kushal, V_9: Prafulla, V_{10}: Gitesh)

Table 4.19. Dry weight of developing panicle (g hill^{-1}) of ten rice cultivars grown in monsoon / *Sali* ecosystem.

	Days after transplanting							
Cultivars	**70**	**77**	**84**	**91**	**98**	**105**	**112**	**119**
Basmuthi	-	0.23g	0.42f	0.91i	3.66j	8.94j	14.15j	-
Bogajoha	-	0.24f	0.40f	0.71j	4.30i	9.04i	14.75i	-
Choimora	-	0.11e	0.25f	1.13g	4.40h	9.08h	15.64g	-
Rashmisali	0.21	0.28d	0.56e	1.70f	5.03f	10.32e	15.20h	-
Lalkalomdani	-	0.27e	0.46f	2.27d	4.88g	9.93g	16.18e	-
Mahsuri	-	0.35a	0.73d	1.12h	5.82d	10.59d	16.36d	-
Moniram	-	0.31c	0.80cd	2.00e	5.51e	11.50b	15.92f	-
Kushal	-	0.34b	0.83c	2.73c	7.14c	10.10f	16.90c	20.88c
Prafulla	-	0.35a	1.47a	3.68a	8.88a	11.30c	18.17b	21.08b
Gitesh	-	0.35a	0.94b	3.31b	8.04b	13.87a	19.70a	21.20a

In each column, means with the similar letters are not significantly different at $P< 0.05$ level by DMRT

Table 4.20. Variation in diameter of medullary cavity (mm) and stomatal frequency (no of stomata mm^{-2}) of ten rice cultivars grown in monsoon / *Sali* ecosystem.

Cultivar	Diameter of medullary cavity (mm)	Stomatal frequency (No. of stomata mm^{-2})
Basmuthi	6.93(± 0.06)a	736(±20)a
Bogajoha	7.21(±0.21)a	637(±33)b
Choimora	6.19(±0.15)b	617(±20)b
Rashmisali	6.39(±0.07)b	577(±20)b
Lalkalomdani	6.01(±0.27)b	597(±23)b
Mahsuri	6.17(±0.070b	498(±20)c
Moniram	5.99(±0.11)b	378(±20)de
Kushal	5.98(±0.24)b	398(±33)d
Prafulla	5.41(±0.09)c	338(±20)de
Gitesh	3.92(±0.05)d	318(±33)e

In each column, means with the similar letters are not significantly different at $P< 0.05$ level by DMRT. Values within parenthesis indicate SEd.

Table 4.21. Yield and yield attributing parameters of ten rice cultivars grown in monsoon / *Sali* ecosystem.

Cultivar	Thousand grain wt (g)	Panicle ($hill^{-1}$)	Panicle dry wt ($g\ hill^{-1}$)	Panicle (m^{-2})	Panicle length (cm)	Spikelet ($panicle^{-1}$)	Filled grain (%)	Yield ($t\ ha^{-1}$)
V1	18.02c	9.25d	14.15j	233.75b	20.98bc	86.50a	76.00c	2.77i
V2	18.10c	9.50cd	14.75i	237.00b	21.45ab	87.25a	76.25c	2.86h
V3	18.57c	9.50cd	15.80g	238.75b	20.55cd	89.00a	76.75bc	3.03g
V4	18.55c	9.75bcd	15.20h	246.00b	19.85ef	87.75a	77.25abc	3.09f
V5	18.75bc	10.25abcd	16.18e	258.75a	20.95bc	87.50a	77.50abc	3.29e
V6	19.38ab	10.50abc	16.36d	262.00a	21.73a	88.50a	77.75abc	3.49d
V7	19.58a	10.75ab	15.92f	264.00a	19.23f	88.25a	78.50ab	3.58c
V8	19.45a	10.50abc	20.88c	262.75a	20.78bc	89.25a	78.75ab	3.59c
V9	19.78a	10.75ab	21.08b	262.75a	20.58cd	88.50a	79.50a	3.66b
V10	20.02a	11.00a	21.20a	267.00a	19.95de	88.75a	79.00ab	3.75a

In each column, means with the similar letters are not significantly different at $P< 0.05$ level by DMRT

Table 4.22. Correlations of physiological and anatomical characteristics of ten rice cultivars with methane emission.

Parameters	Correlation with methane emission
Plant height	0.41**
Leaf number	0.74**
Leaf area	0.98**
Tiller number	0.85**
Leaf blade dry weight	0.57**
Leaf sheath dry weight	0.57**
Culm dry weight	0.16**
Shoot dry weight	0.41**
Root dry weight	0.49**
Root volume	0.67**
Root length	0 62**
Photosynthesis	0.50**
Diameter of medullary cavity	0.84**
Stomatal frequency	0.95**
Transpiration	0.99**
Soil organic carbon	0 84**
Soil pH	0.74**
Soil temperature	NS

** = Correlation is significant at the 0.01 level of significance; NS= Non significant.

4.4.20. Stomatal frequency (No. of stomata mm^{-2})

Higher stomatal frequencies were exhibited by Basmuthi ($736mm^{-2}$) and Bogajoha ($636mm^{-2}$), whereas Prafulla ($338\ mm^{-2}$) and Gitesh ($318\ mm^{-2}$) showed lower stomatal frequencies (Table 4.20; Plate 4.2). Significant positive correlation was recorded between methane emission and stomatal frequency of different rice cultivars (Table 4.22).

4.4.21. Transpirational rates

Transpirational rates of the cultivars were recorded at weekly interval and are presented in Table 4.18. Significant cultivar differences were observed in the rate of transpiration at different growth stages of the crop. High and medium CH_4 emitting cultivars recorded higher rate of transpiration compared to low emitting varieties.

4.4.22. Yield

Data recorded on yield and yield attributing parameters of the cultivars are presented in Table 4.21. Variety Gitesh recorded higher grain yield ($3.75t\ ha^{-1}$) followed by Prafulla ($3.66t\ ha^{-1}$) and Kushal ($3.59t\ ha^{-1}$). On the other hand, Basmuthi recorded lower grain yield ($2.77t\ ha^{-1}$) compared to other rice cultivars. Thousand grain weight ($g\ hill^{-1}$), filled grain (%), panicle $plant^{-1}$, spikelet $panicle^{-1}$, number of panicle (m^{-2}), panicle dry weight ($g\ hill^{-1}$) were higher in low CH_4 emitting cultivars Prafulla, Kushal and Gitesh compared to Basmuthi, Bogajoha, Choimora and Rashmisali (high CH_4 emitting cultivars).

Chapter 5

Discussion

5. DISCUSSION

There are three processes of CH_4 release in to the above ground atmosphere from rice fields: (i) methane release as bubbles, (ii) diffusion of methane across the water surface, and (iii) transport of CH_4 through the rice plant and then emission to the atmosphere. Emission through rice plant has been reported as the most important phenomenon (Wassmann *et al.*, 2000). Results obtained from the present investigation on plant mediated methane emission from rice fields are discussed below.

1. Seasonal and cultivar variation in methane emission

In the present investigation, methane emissions from paddy fields were evaluated from three different agroecosystems, *viz.* monsoon (*Sali*), irrigated (*Boro*) and rainfed upland (*Ahu*) rice agroecosystems. Among the three rice growing agroecosystems, higher seasonal integrated methane flux (E_{sif}) was recorded in the monsoon / *Sali* rice agroecosystem followed by irrigated / *Boro* and rainfed upland / *Ahu* rice agroecosystems. Cultivar differences in methane emission were observed irrespective of agroecosystems. Despite this difference, similar pattern of CH_4 emission from the cultivars was observed. In all agroecosystems, methane flux was initially very low and then increased with advancing age of the rice plants. Two distinct methane emission peaks were detected; the first was during active vegetative growth and the second at panicle initiation stage of the crop. Methane emissions declined after panicle initiation stage and were negligible at harvest. This trend of methane emission was observed in all the agroecosystems independent of the cultivars.

The low emission of methane after transplanting might be due to the limited carbon sources, low levels of methanogenesis and poor conduction of methane from the soil to the atmosphere through rice plants with under-developed biomass (Adhya *et al.*, 1994). Some workers reported an initial methane emission maximum that occurs shortly after

transplanting, apparently caused by the fermentation of easily degradable soil organic matter in the soil (Sass and Fisher, 1992). However, if the amount of easily degradable carbon is low at the beginning of the season, no initial peak of methane emission is reported to develop (Neue *et al.*, 1995). In the present study irrespective of agroecosystems and cultivars, no distinct peaks were detected soon after transplanting, which may be due to low amount of soil organic carbon (Fig. 4.3; 4.14; 4.24; Table 4.13) as suggested by Neue *et al.* (1995). Methane formation during the early and mid-season growth stages of rice results primarily from microbial decomposition of freshly incorporated crop residues (Wassmann *et al.*, 2000). Therefore, the first methane emission peak, observed at active vegetative growth stage of the cultivars irrespective of the agroecosystems might be associated with decomposition of organic matter derived from left over plant residues in the form of paddy straw and dead roots from the previous crop, which served as substrate for methanogenes (Xu *et al.*, 2000). The second highest CH_4 flux maxima observed in the present investigation, during the panicle initiation stage, can be attributed to the higher availability of substrates in the rice rhizosphere as suggested by Adhya *et al.* (1994) and Mitra *et al.* (2005). Root exudates provide important carbon sources for CH_4 production by supplying energy for microbial activity in rice growing soil. Dissolved organic carbon in the soils of rice root zone increased with plant growth, whereas in the soils without rice plant, it remained low throughout the growing season (Lu *et al.*, 2000), indicating that the primary source of this carbon fraction was plant derived. Increased organic matter input through root exudates and decaying roots might be responsible for the second methane emission maxima at panicle initiation stage of the cultivars irrespective of agroecosystems observed in the present investigation, a mechanism suggested by Bouwman (1991) and Wassmann *et al.* (1993). Drop in methane emission observed in the present investigation at the end of the crop growth period can be attributed to limited carbon availability (Fig. 4.3; 4.14; 4.24; Table 4.13), decline in gas transport capacities due to reduction of leaf area (Table 4.1; 4.5; 4.14; Fig. 4.27) and tiller number(Table 4.1; 4.5; 4.9; 4.14) and reduction in conductance of

the roots due to reduction of root growth (Fig. 4.7; 4.17; 4.28; Table 4.15) as suggested by Nouchi *et al.* (1994).

2. Soil factors and methane emission

Various physico-chemical characteristics of soil have been found to influence CH_4 emissions from paddy fields through their effect on CH_4 production. Soil organic carbon contents of the experimental plots were initially low, reached a maximum at late tillering and panicle initiation stage of the crop. This trend was observed in all the agroecosystems for all the cultivars (Fig. 4.3; 4.14; 4.24; Table 4.13). Higher soil organic carbon content was recorded in plots of high methane emitting cultivars. In these cultivars, higher amount of photosynthate was portioned to the root (Fig. 4.9; 4.19; 4.30; Table 4.17) which may enter the root-zone soil in the form of rhizo-deposition, a mechanism suggested by Lynch and Whipps (1990) and Marschner (1996). Incorporation of higher amount of photosynthetic carbon in to the soil increased the soil organic carbon content (Jimenez and Lal, 2006) in plots grown with high methane emitting cultivars resulting in higher methane flux (Fig. 4.1; 4.12; 4.22; 4.33; Table 4.12).

It is evident that regulation of seasonal variation of CH_4 flux was under the control of organic carbon available in the soils. A highly significant positive correlation was found between methane emission and soil organic carbon content in all the agroecosystems (Table 4.4; 4.8; 4.11; 4.22). Lu *et al.* (2000) also established a similar trend and reported that the change in methane emission was closely related to the change in organic carbon concentration in the root zone. Towards the end of the crop growth, when methane emission was negligible, soil organic carbon also recorded lower values in all the cultivars irrespective of ecosystems. Carbon loss from soils could not be compensated by the carbon input through plant photosynthesis (Zhongjun *et al.*, 2006) because the increase in soil organic carbon was less than the net plant carbon input (Lu *et al.*, 2002). Decrease in photosynthate partitioning to root at the end of the season recorded in the present investigation (Fig.4.9; 4.19; 4.30;

Table 4.17) and concomitant reduction of incorporation of plant derived carbon in to the soil (Lu *et al.*, 2000) can be attributed to decline in organic carbon at this stage of crop growth.

The anaerobic and reduced soil condition is congenial for methane production in rice soils (Sass *et al.*, 1990; Mathews *et al.*, 1991). The physico-chemical characteristics of transplanted rice soils get changed after flooding. Reduced level of oxygen supply cannot meet the demand of the aerobic organisms, whereas anaerobic organisms start to proliferate under anoxic soil environment. Under such circumstances, the redox potential of soil drops sharply and CO_2 and HCO^-_3 concentrations increase to very high levels. As a result, the pH of acid soils increases after flooding and stabilize between 6.5 and 7.2 (Wang *et al.*, 1993). Changes in soil pH were regularly monitored in all the experiments. Soil pH started to increase after transplanting and then there was a decreasing trend of soil pH during the crop maturation stage till harvest. The pH of the soils grown with the rice cultivars ranged between near neutrality throughout the growing period irrespective of ecosystems (Fig. 4.5, 4.15, 4.26), which were favorable for methanogenesis (Wang *et al.*, 1992). The lowest value (pH 5.37) was recorded in monsoon / *Sali* rice growing season (in 2005) at 7 DAT, which later tended to reach near neutrality and attained the highest value (pH 6.34) with prolonged submergence at 63 DAT (Fig. 4.5). Methane flux values are correlated with soil pH in monsoon / *Sali* and irrigated / *Boro* ecosystems (Table 4.4; 4.8; 4.22). The findings of the present investigation are in conformity with the results obtained by Parashar *et al.* (1991).

Rice is grown under a wide range of water regimes from upland to deep-water conditions. The rice plant is adapted to submerged anaerobic soil conditions because of its unique air pathway from leaves to roots. On the other hand, methane production is promoted by anaerobiosis created in rice soil due to submergence (Lindau *et al.*, 1993). In the present investigation, considerable amount of standing water was recorded in the field during the crop growth period in all agroecosystems, creating anaerobic situations favorable for methane production. Among different ecosystems, higher amount of rainfall was recorded during monsoon / *Sali* rice growing season, which created a favorable environment for

higher methane production (Fig. 3.2; 3.3). During this season, seasonal rainfall kept the experimental field submerged during the crop growth period (Fig. 4.2) in both the years (up to 105 DAT in 2005 and 98 DAT in 2006). Standing water in the experimental fields during monsoon season is one of the factors for higher emission from the *Sali* rice ecosystem and this is supported by the findings of Yagi and Minami (1990), Sass *et al*, (1990) and Rath *et al.* (1999a).

In *Sali* rice growing period, higher soil temperature was observed at the initial and mid season of the crop, but with the advancement of growth and development of the crop, soil temperature decreased gradually and reached lower values at the crop maturation stage (Fig. 4.4). In contrast, during the *Boro* rice growing season, at initial stage of crop growth, lower soil temperature was observed, but with the advancement of growth and development of the crop soil temperature increased gradually and reached higher values at maturity (Fig. 4.13). This wide range of temperature variation might be a reason of relatively lower methane emission in irrigated spring / *Boro* rice as compared to monsoon / *Sali* rice. Most of the methanogenes are mesophilic with temperature optima of 30 to 40^0 C (Nouchi *et al.*, 1990). Relatively higher soil temperatures at the initial stage and at the mid season may be one of the causes of higher methane flux in monsoon / *Sali* rice compared to spring / *Boro* rice agroecosystem. The methanogenic bacteria in monsoon season experiences high optimum temperature, required for methane production a mechanism proposed by Nouchi *et al.*, (1990). The same concept holds good for our study also where we report more emission of methane in the monsoon / *Sali* season. Moreover, the higher soil temperatures during *Sali* rice growing season stimulated organic matter degradation which favoured methane production. Hence, during *Sali* season higher seasonal methane flux (E_{sif}) was obtained. Although in upland / *Ahu* rice growing season, favourable soil temperatures for methanogenesis were recorded, low E_{sif} values were observed in this agroecosystem. This is primarily because of plant factors such as lower leaf area (Table 4.1; 4.5; 4.14; Fig. 4.27), tiller number (Table 4.1; 4.5; 4.9; 4.14) and reduced root growth (Fig. 4.7; 4.17; 4.28; Table

4.15) of *Ahu* rice cultivars, which reduced plant mediated transport and release of methane. Shorter crop duration of *Ahu* rice cultivars (77 days from transplanting to harvest) compared to *Sali* (119 days) and *Boro* (112 days) rice cultivars was another contributing factor of lower seasonal integrated methane flux recorded in upland / *Ahu* ecosystem. Similar findings have been reported for long and short duration cultivars by Adhya *et al.* (1994).

3. Methane emission and morphology of rice plant

Rice plants are primarily responsible for transport of methane from the reduced soil to the atmosphere (Wassmann *et al.*, 2000). Rice plants have there major functions in regulating the CH_4 budget: (i) as a source of methanogenic bacteria (ii) as a conduit for CH_4 through a well developed system of intercellular air spaces and (iii) as a active CH_4 oxidizing site in the rice-rhizosphere by supporting O_2 counter transport (Aulakh *et al.*, 2002). Therefore, the morphology of different genotypes of rice is closely associated with the regulation mechanism of methane emission to the above ground atmosphere (Gogoi *et al.*, 2005).

Detail study of the growth parameters of rice cultivars have shown that there exists a close relationship of morphological parameters of rice plant with methane emission. In the present investigation, methane emission was found to be positively correlated with the root growth in all the cultivars irrespective of agroecosystems (Table 4.4; 4.8; 4.11; 4.22). Methane production from soils planted with rice plant was found to be higher than that of the unplanted soils (Zhongjun *et al.*, 2006), which indicates a direct role of rice root on methane production. Rice cultivars grown during monsoon / *Sali* and irrigated / *Boro* seasons had higher root vigour compared to upland / *Ahu* rice-growing season. Larger root biomass during *Sali* and *Boro* season may contribute to production of more root exudates and root litters. Root exudates refer to organic materials released by roots into the surrounding soil and consist mainly of carbohydrates, organic acids, amino acids and phenolic compounds (Marschner, 1986) that provide the substrates to the microbial community (Neue *et al*, 1997)

and enhance methane production (Vogel *et al.*, 1988). Larger root litter in the form of sloughed off root cap cells and higher exudation from larger root biomass may enhance methane emission in monsoon / *Sali* and irrigated / *Boro* rice ecosystem, a mechanism suggested by Sass *et al.* (1990). In the present investigation, high methane emitting cultivars recorded higher root growth in terms of length, volume and dry weight, irrespective of ecosystems. Amount of root exudates was reported to be positively correlated to root dry matter production (Wang and Adachi, 2000), and therefore, higher root weight recorded in the high emitting cultivars increased the methane production and transport (Ladha *et al.*, 1986). Therefore, it can be assumed that cultivars with higher root biomass provide higher substrate to the methanogenes resulting in higher methane production. Therefore the cultivar variation in methane emission observed in the present study can also be attributed to the differences in nature of root growth of the cultivars as suggested by Sass *et al.* (1990).

Leaf area and dry matter of leaf blade, leaf sheath and culm are reported to be associated with conductance of methane (Nouchi *et al.*, 1994). In the present investigation, dry weight of leaf blade, leaf sheath and culm of different rice cultivars was measured (Table 4.4; 4.8; 4.11; 4.16) and a relationship of methane flux with these parameters had been observed. Increase in biomass during plant growth until flowering determines the corresponding increase in methane transport capacity (Aulakh *et al.*, 2002). In the present study, plant biomass production and methane emission were found to be positively correlated (Table 4.4; 4.8; 4.11; 4.22). Cultivars with higher plant biomass recorded higher methane emission, irrespective of the ecosystems. Our results are supported by the findings of Sass *et al.*, (1991). A positive correlation of methane emission with leaf number, leaf area and leaf area index (LAI) was recorded in all the ecosystems independent of rice cultivars. Irrespective of the agroecosystems, cultivars with more leaf number and larger leaf area recorded higher methane emission. Higher leaf number and leaf area index of monsoon / *Sali* and irrigated (*Boro*) rice cultivars provide larger area for methane release in to the environment compared to upland / *Ahu* rice cultivars. Moreover, all the cultivars recorded higher LAI during the panicle initiation stage, which is one of the reasons for more methane

flux during that period. Similar results of cultivar differences in leaf area and methane emission were reported by Nouchi (1994) and Gogoi *et al.*, (2005). Dissolved methane in the soil water diffuses into the cell-wall water of the root cells, gasifies in the root cortex and then is transported through plant and released into the environment (Nouchi *et al.*, 1990). The rice culm, leaf sheath and leaf blade provide the major release pathway of methane to the atmosphere (Nouchi, 1994). Therefore, results of the present investigation have shown that tiller number can be a major regulating factor of plant mediated methane transport. Profuse tillering increases the total intercellular air spaces of rice plants, which will provide larger cross sectional area for plant mediated methane transport to the atmosphere. In the present investigation, rice cultivars with more tillers released more methane into the atmosphere. These results are supported by the findings of Neue *et al.* (1996) and Mariko *et al.* (1991). Positive correlation of methane emission with tiller number in all the ecosystems obtained in the present study is a strong evidence to support this concept (Table 4.4; 4.8; 4.11; 4.22). These results are in conformity with the findings of Aulakh *et al.* (2002). This is one of the reasons for cultivar differences in methane emission recorded in the present study. Therefore, it is logical to assume that plants with less number of tillers would minimize CH_4 emission from the soil to the atmosphere.

4. Methane emission and anatomical characteristics of rice plant

In the present investigation, attempts were made to establish a relationship of methane emission with anatomical characteristics of rice plants. Anatomical study of ten rice cultivars grown in monsoon rice ecosystem revealed significant differences in the size of the medullary cavity among the cultivars (Plate 4.1; Table 4.20). High methane emitting cultivars recorded significantly greater size of medullary cavity compared to medium and low emitting ones. Methane concentrations in the medullary cavities of rice plants are reported to be about 2900 times higher than that of ambient air (Nouchi *et al.*, 1990). Therefore, it is possible that methane may diffuse and move upward through the shoots via

the medullary cavity along concentration gradients. Since methane emission is diffusion controlled process, it is hypothesized that larger size of the medullary cavities in the cultivar Basmuthi and Bogajoha may increase the cross-sectional area of the methane diffusion pathway. On the other hand, smaller medullary cavities of Prafulla and Gitesh may restrict the methane flow by reducing the cross sectional area. This may be one of the reasons of higher methane emission from Basmuthi and Bogajoha. These findings suggest that the wide variation in methane emission among rice cultivars may be associated with the anatomical features of the medullary cavity, which is further strengthened by observed positive correlation between methane flux and the size of medullary cavity (Table 4.22). Our findings on the role of medullary cavity in methane emission are supported by the report of Yao *et al.* (2000) that methane transport was correlated with inter-cellular volume of stem.

Numerous stomata were detected at the adaxial surface of the rice leaves from the experimental field. Scanning Electron microscopy (SEM) showed higher stomatal frequencies in the leaves of high methane emitting cultivars (Plate 4.2; Table 4.20). Methane emission is found to be positively correlated with stomatal frequency (Table 4.22). The stomata of leaf blade is one of the release sites of methane in to the atmosphere. As discussed above, high methane emitting cultivars recorded higher tiller number and larger leaf area compared to low methane emitting varieties. It may be hypothesized that since leaf-stomata is one of the release sites of methane, higher tiller number and leaf area with higher stomatal frequency provide more cross sectional area for release of methane from the plant body to the atmosphere. Neue *et al.* (1997) reported that before shoot elongation, about 50% of the methane is released from leaf blades. Although micropores, present in the basal portion of leaf sheath, were described as the main site of methane release by Nouchi *et al.* (1990), it was also pointed out by them that the micropores, surrounded by sclerenchyma, are not linked to the lysigenous intercellular space. Moreover, the presence of micropores in the leaf sheath was not confirmed by other workers (Butterbach-Bahl *et al.*, 2000) and such differences in findings might be attributed to the inherent genetic traits of the rice cultivars used in the studies (Wang *et al.*, 1997). The intercellulars, located between the epithelial

cells and closely related to the leaf sheath stomata may have a crucial role in plant mediated methane transport (Butterbach-Bahl *et al.*, 2000) and a link of the stomata with the lacunae via these intercellulars is assumed logically. Therefore, stomata of the leaf sheaths are also suggested to be one of the sites of methane release (Butterbach-Bahl *et al.*, 2000). Similar mechanism may operate in the leaf blade also and might be the reason for the relationship of methane emission with leaf area and stomatal frequency (Table 4.22).

Significant positive correlations between transpiration and methane emission (Table 4.22) in the rice varieties have been observed. High methane emitting cultivars exhibited higher transpirational rate than the low emitting varieties (Table 4.18). Allen *et al.* (2003) recorded that methane emission coincides with increased transpirational rate indicating that soil water flow to the roots deliver more dissolved methane to the rice plant during periods of rapid transpiration. Diel rates of CH_4 emissions were also found to be linked with the transpiration induced bulk flow (Chanton *et al.*, 1997). From the data recorded on stomatal frequency, leaf area and transpirational rate, it can be hypothesized that a fraction of methane may be released into the environment due to transpiration-induced bulk flow, although methane is transported within the rice plant predominantly via molecular diffusion (Wang *et al.*, 1997). It may be noted that all the traditional rice cultivars examined in this investigation recorded higher leaf area and tiller number with higher transpirational rate and bigger medullary cavity and found to emit more methane compared to the high yielding improved varieties. The transport mechanism of methane to stomata from the lacunae via intercellulars is not well understood. This intercellular mechanism can be described with more sophisticated methodologies, e.g. use of radio-tracer techniques for clear understanding of plant mediated methane transport.

5. Methane emission and photosynthetic characteristics of rice plant

Methane emission and photosynthetic characteristic of rice are reported to be closely related (Denier van der Gon *et al.*, 2002; Sass and Cicerone, 2002). Elevated CO_2 induced

higher photosynthate production was found to increase methane emission (Weiguo *et al.*, 2006) from rice plant. In the present investigation, photosynthetic rates of different rice cultivars grown in different ecosystems were recorded at weekly interval. As discussed above, a major portion of the net photosynthetic carbon is allocated to the root and a significant amount of this fraction enters the soil in the form of rhizo-deposition. Subsequently, a part of this rhizo-deposition will be transformed to methane (Jimenez and Lal, 2006), and as much as 4.5% of photosynthetically fixed carbon can be released as methane into the atmosphere (Huang *et al.*, 2002). In our work, higher photosynthetic rates were recorded in high emitting cultivar at the vegetative stage (Fig. 4.10; 4.20; 4.31; Table 4.18) of crop growth. Higher photosynthetic rate resulted in profuse vegetative growth in the form of larger leaf area (Table 4.1; 4.5; 4.14; Fig. 4.27) and root length (Fig. 4.7; 4.17; 4.28; Table 4.15) and volume (Fig.4.8; 4.18; 4.29; Table 4.15), which in turn would support extensive methanogenesis via an enhanced assimilate discharge into the soil (Lu *et al.*, 2002; Weiguo *et al.*, 2006; Wang and Adachi, 2000) and thus gas absorption. The percentage distribution of photosynthetically derived assimilates to soil was exponentially correlated to the rate of root growth (Lu *et al.*, 2002). Greater root growth provides greater surface area for diffusion of CH_4 into roots and greater air space (Singh *et al.*, 1999), which might be the reason for enhancement of CH_4 emission from rice cultivars having higher photosynthetic rates during the vegetative growth period. Dry weight of above ground plant parts of high emitting cultivars also significantly higher, and as discussed in the earlier section, larger aboveground biomass signifies the conduit effect of rice plants (Mariko *et al.*, 1991). Comparatively lower photosynthetic rates recorded in low methane emitting cultivars during vegetative growth period lead to reduced vegetative growth, which resulted in low methane emission.

After panicle initiation, photosynthetic rate was higher in low methane emitting cultivars. Despite higher photosynthetic rate, those cultivars recorded lower methane emission during this period. This trend can be explained in terms of preferential translocation of photosynthate towards the developing panicle (Fig. 4.11; 4.21; 4.32; Table

4.19) rather than the root system (Denier van der Gon *et al.* 2002). Lower vegetative growth of low emitting cultivars in terms of smaller leaf area, reduced leaf number, lower root length and volume, and lower dry weight of different plant parts may be attributed to lower methane emission during this period. On the other hand, in high emitting cultivars, translocation of higher amount of photosynthate towards the vegetative parts during the reproductive phase resulted into larger root and shoot growth which enhanced methane emission.

6. Methane emission and grain yield of rice

During the entire course of investigation, apart from evaluating the methane emission potential of rice varieties, their grain yield potential were also recorded (Table 4.3; 4.7; 4.10; 4.21). It was found that cultivars with low methane emission exhibited better yield potential in agroclimatic condition of Assam. Higher values of thousand grain weights, number of panicle m^{-2}, filled grain percentage and higher yield were recorded in low methane emitting cultivars, indicating higher photosynthate partitioning towards the developing grains. A major portion of photosynthesized carbon, not partitioned to rice grains, is emitted as methane (Denier van der Gon *et al.*, 2002), and therefore an inverse relationship exists between rice plants' capacity to store photosynthetically fixed carbon and seasonally emitted methane (Sass and Cicerone, 2002), which supports the findings of the present investigation. Dry weight of developing panicle was also found to be higher in low emitting cultivars during the whole grain filling period. Higher rate of photosynthesis during the reproductive stage, along with efficient translocation of assimilates to the grain, as evident by the superior yield attributing parameters, might be the reason of better grain yield in low methane emitting cultivars. On the other hand, high emitting cultivars exhibited lower yield and inefficient yield developing attributes. This indicates that in high methane emitting cultivars, photosynthesized carbon could not be allocated efficiently to the developing grain. Cereal grain yield can be limited either by the supply of assimilate to fill the grain (source

limitation) or by the capacity of the reproductive organs to accept the assimilate (sink limitation) (Denier van der Gon *et al.*, 2002). In high methane emitting cultivars, lower photosynthetic rate during the reproductive stage indicated source limitation, whereas low yield development, in spite of higher availability of pre-anthesis reserves reflected sink limitation. Lower efficiency of stored photosynthates translocation from different plant parts, inferior capacity of current assimilates supply to the developing grain, along with lower photosynthetic rate, resulted in lower yield in the high methane emitting cultivars. The amount of carbon, not allocated to the developing grain, reflects the yield gap and a portion of the photosynthetically assimilated carbon associated with the yield gap entered the soil as rhizo-deposition. This resulted in higher substrate availability of methanogenes and this might be a major reason for more emission of methane from these cultivars, a mechanism supported by Denier van der Gon *et al.* (2002).

It can be proposed that while selecting rice genotypes for low methane emission, yield potential of a cultivar has to be taken care of which is the most important trait of a genotype from agricultural point of view. The findings of the present investigation indicate that the use of high-yielding cultivars with higher photosynthate carbon translocation towards the grain would result in lower methane emission. Therefore, screening of existing rice cultivars, and initiation of breeding programme for new cultivars with higher photosynthate carbon translocation towards the grain and low photosynthate partitioning to the vegetative parts could offer an important methane mitigation option. Rice cultivars having higher photosynthate carbon allocation capacity to the grain and lower translocation of carbon to root for methanogenes might help to reduce methane emission from paddy fields, without compromising the grain yield. Therefore, development of new plant type of rice with a balance in source and sink capacity may be important in mitigating methane emission from paddy field.

Chapter 6

Summary and Conclusion

6. SUMMARY AND CONCLUSION

This experiment was carried out to evaluate the methane emission from rice paddies at different agroecosystems of North Bank Plain Agroclimatic Zone of Assam. Attempt was also made to establish a relationship of CH_4 emission with physiological and anatomical characteristics of rice plant. Following conclusions have been drawn from the results of the experiments and the findings are summarized below.

1. Two-years (2005 and 2006) of measurement of methane flux from rice varieties Bahadur and Piolee grown in rainfed monsoon (*Sali*) agroecosystem (August-November) indicated higher methane flux from variety Bahadur compared to Piolee irrespective of growth stages.

2. Two-years (2006 and 2007) of measurement of methane flux from rice cultivars Agni and Ranjit grown in irrigated agroecosystem (February- June) indicated higher methane flux form cultivar Agni compared to Ranjit. Higher seasonal integrated methane flux (E_{sif}) was recorded from cultivar Agni (E_{sif} in 2006: 7.15g m^{-2}; E_{sif} in 2007: 7.42g m^{-2}) compared to Ranjit (E_{sif} in 2006: 5.42g m^{-2}; E_{sif} in 2007: 5.76g m^{-2}).

3. Measurement of methane flux from two different rice varieties Disang and Luit grown in rainfed upland agroecosystem (April - July) indicated higher seasonal integrated methane flux from variety Disang (E_{sif}: 1.38g m^{-2}), compared to Luit (E_{sif} : 0.96g m^{-2}).

4. Measurement of CH_4 flux from ten rice cultivars grown in rainfed monsoon (*Sali*) agroecosystem (August-November) indicated highest seasonal integrated CH_4 flux from cultivar Basmuthi (E_{sif}: 12.46g m^{-2}) and lowest from Gitesh (E_{sif}: 8.74g m^{-2}). The traditional rice cultivars exhibited higher methane emission than the improved, high yielding rice varieties.

5. Among the three rice growing ecosystems, monsoon rice agroecosystem (*Kharif* / *Sali*) emitted maximum methane followed by irrigated Boro (Spring rice) and rainfed upland (Summer / *Ahu*) rice agroecosystems.

6. Methane flux was initially low and then increased with advancing age of the rice plants. Two distinct methane emission peaks, first at active vegetative growth, and the second at panicle initiation stage were detected. Emission was very low at harvest. This trend of methane emission was recorded in all the rice cultivars irrespective of the ecosystems.

7. Results of the present investigation revealed that regulation of seasonal variation of methane flux was under the control of organic carbon available in the soils. Soil organic carbon contents of the experimental plots were initially low, reached a maximum at late tillering and panicle initiation stage of the crop when higher methane emissions were recorded. This trend was observed in all the agroecosystems for all the cultivars. In high methane emitting cultivars, higher amount of photosynthate was partitioned to the root which may enter the root-zone soil in the form of rhizo-diposition, thereby increasing the soil organic carbon content resulting in higher emission.

8. It has been observed in the present study that the cultivars with profuse vegetative growth recorded higher methane flux values. Higher tiller number, leaf number, leaf area index, root length, root volume positively influenced methane emission.

9. Anatomical study of ten rice cultivars grown in monsoon rice ecosystem showed that high methane emitting cultivars recorded greater size of medullary cavity compared to medium and low emitting ones. A positive correlation of methane flux with the size of medullary cavity, stomatal frequency and transpirational rates were observed. It is hypothesized that a fraction of methane may be transported with transpiration-induced bulk flow and released

into the environment through stomata. All the traditional rice cultivars examined in this investigation recorded higher leaf area and tiller number with higher transpirational rate and larger medullary cavity emitted more methane compared to the high yielding improved varieties.

10. Grain yield and yield-related parameters such as increased photosynthate partitioning to panicles were greater in low methane emitting cultivars. In higher methane emitting cultivars, greater diversion of photosynthates to vegetative parts, at both vegetative and reproductive stages of the crop, enhanced methane emission from the soil to the above ground atmosphere.

The study concluded that the methane emission from paddy fields depends on the type of rice agroecosystem. Methane emission is also regulated by phenological, physiological and anatomical characteristics of rice cultivars. Methane emission from monsoon rice (*Sali*) agroecosystem was found to be higher among all the agroecosystems. But this agroecosystem is most popular among the farmers of Assam. Therefore, methane emission from *Sali* rice needs to be minimized since this ecosystem has greater methane emission potential. In this respect, findings of this study suggest the possibility of reducing methane emission through judicious selection of plant characters. However, while selecting rice cultivars as a biological mitigation option, yield potential of a cultivar must be considered because it is the most important end value of a genotype from the economical point of view. Therefore, development of new plant type of rice with balance source and sink capacity may be important in mitigating methane emission from paddy field. Results of the present investigation indicate that cultivation of high-yielding cultivars with low photosynthate carbon translocation towards the vegetative parts of the plant would result in lower methane emission. Therefore, screening of existing rice cultivars, and initiation of breeding programme for new improved varieties with low photosynthate partitioning to vegetative part could offer an important methane mitigation option. Rice cultivars having

higher photosynthate carbon allocation capacity to rice grain and lower translocation of carbon to root for methanogenes might help to reduce methane emission from paddy fields, without compromising the grain yield. Therefore, incorporation of these plant traits identified in the present investigation could help the plant breeding programme for high yielding rice plants with low methane emission potential.

Bibliography

BIBLIOGRAPHY

Adachi K (1999) Isolation of hydrogenotrophic methanogenic archaea from a subtropical paddy field. *FEMS Microbiology Ecology,* **30:** 77-85.

Adhya TK, Pattnaik P, Satpathy SN, Kumaraswamy S and Sethunathan, N (1997) Influence of phosphorus application on methane emission and production in flooded paddy soils. *Soil Biology and Biochemistry,* **30:** 177-181.

Adhya TK, Rath AK, Gupta PK, Rao VR, Das SN, Parida KM, Parashar DC. and Sethunathan N (1994) Methane emission from flooded rice fields under irrigated conditions. *Biology and Fertility of* Soils, **18**: 245-248.

Adhya TK, Bharati K, Mohanty SR, Ramakrishnan B, Rao VR, Sethunathan N and Wassmann R (2000) Methane emission from rice fields at Cuttack, India. *Nutrient Cycling in Agroecosystems,* **58:** 95-105.

Allen LH Jr, Albrecht SL, Colon-Guasp W, Covell SA, Baker JT, Pan D and Boote KJ (2003) Methane emissions of rice increased by elevated carbon dioxide and temperature. *Journal of Environmental Quality,* **32**: 1978-1991.

Anastasi C, Dowding M and Simpson VJ (1992) Future CH_4 emissions from rice production. *Journal of Geophysical Research,* **97**: 7521-7525.

Aulakh MS, Bodenbender J, Wassmann R and Rennenberg H (2000a) Methane transport capacity of rice plants. I. Influence of methane concentration and growth stage analyzed with an automated measuring system. *Nutrient Cycling in Agroecosystems,* **58:** 357-366.

Aulakh MS, Wassmann R, Rennenberg H and Fink S (2000b) Pattern and amount of aerenchyma relate to variable methane transport capacity of different rice cultivars. *Plant Biology,* **2:** 182-194.

Aulakh MS, Wassmann R and Reenberg H (2001) Methane emissions from rice fields quantification, mechanisms, role of management and mitigation options. *Advances in Agronomy*, **70:** 193-260.

Aulakh MS, Wassmann R, Bueno C and Rennenberg H (2001a) Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa* L.) on methane production in a paddy soil. *Plant and Soil*, **230**: 77-86.

Aulakh MS, Wassmann R and Rennenberg H (2002) Methane transport capacity of twenty two rice cultivars from five major Asian rice growing countries. *Agriculture, Ecosystems and Environment*, **91:** 59-71.

Babu YJ, Li C, Frolking S, Nayak DR, Adhya TK (2006) Field validation of DNDC model for methane and nitrous oxide emissions from rice-based production systems of India. *Nutrient Cycling in Agroecosystems*, **74:** 157-174.

Bachelet D and Neue HU (1993) Methane emission from wetland rice areas of Asia. *Chemosphere*, **26:** 219-238.

Baig MJ, Swain P and Murty KS (1998) The photosynthetic efficiency of some elite rice hybrids and restorers. *Photosynthetica*, **35:** 241-246.

Banik A, Sen M and Sen SP (1996) Effects of inorganic fertilizers and micronutrients on methane production from wetland rice (*Oryza sativa* L.). *Biology and Fertility of Soils*, **21:** 319-322.

Banker BC, Kludze HK, Alford DP, DeLaune RD and Lindau CW (1995) Methane sources and sinks in paddy rice soils: Relationship to emissions. *Agriculture, Ecosystems and Environment*, **53:** 243-251.

Baruah KK, Parashar DC, Gupta PK, Sharma C, Sharma RC, Jain MC and Mitra, AP (1997) Effect of water management and rice genotypes on methane emission from paddy field. *India Journal of Radio Space Physics*, **26:** 77-81.

Baruah KK, Gogoi N, Gogoi B, Goswami S, Barman B and Gupta PK (2002) Plant and soil factors associated with methane emission from irrigated rice ecosystem of Assam. *In:* Van Ham *et al.* (Eds.) Non CO_2 green house gases: Scientific Understanding, Control and Policy Aspects. Mill Press, The Netherlands. pp. 101-106.

Batjes NH, Bridges EM (1992) A review of soil factors and processes that control fluxes of heat, moisture, and greenhouse gases. Technical Paper 23, International Soil Reference and Information Centre, Wageningen.

Beckett PM, Armstong W, Justin SHFW and Armstong J (1988) On the relative importance of convective and diffusive gas flows in plant aeration. *New Phytologist*, **110:** 463-468.

Bender M and Conrad R (1992) Kinetics of CH_4 oxidation in oxic soils exposed to ambient air or high CH_4 mixing ratios. *FEMS Microbiology Ecology*, **101:** 261-270.

Bender M and Conrad R (1993) Kinetics of methane oxidation in oxic soils. *Chemosphere*, 26: 687-696.

Bender M and Conrad R (1995) Effect of CH_4 concentrations and soil conditions on the induction of CH_4 oxidation activity. *Soil Biology and Biochemistry*, **27:** 1517-1527.

Bharati K, Mohanty, SR, Singh DP, Rao VR and Adhya TK (2000) Influence of incorporation or dual cropping of *Azolla* on methane emission from a flooded alluvial soil planted to rice in eastern India. *Agriculture, Ecosystems and Environment*, **79:** 73-83.

Bharati K, Mohanty SR, Rao VR and Adhya TK (2001) Influence of fooded and non fooded conditions on methane efflux from two soils planted to rice. *Chemosphere: Global Change Science*, **3:** 25-32.

Bhatia A, Pathak H and Aggarwal PK (2004) Inventory of methane and nitrous oxide emissions from agricultural soils of India and their global warming potential. *Current Science*, **87**: 317-324.

Black CA (1965) Methods of soil analysis, Part I. Agronomy Monograph, 9: 578-603.

Blaut M (1994) Metabolism of Methanogenes. Antonie Van Leeuwenhoek, 66: 187- 208.

Bodelier PLE, Roslev P, Henckel T and Frenzel P (2000) Stimulation by ammonium based fertilizers of methane oxidation in soil around rice roots. *Nature*, **403:** 421-424.

Born M, Dorr H and Levin J (1990) Methane consumption in aerated soils of the temperate zone. *Tellus B*, **42:** 2-8.

Bosse U and Frenzel P (1997) Activity and distribution of methane oxidizing bacteria in flooded rice soil microcosms and in rice plants *(Oryza sativa* L.*)*. *Applied and Environmental Microbiology*, **63:** 1199-1207.

Bousquet P, Ciais P, Millwe JB, Dlugokencky FJ, Hauglustaine DA, Prigent C, Van der Werf GR, Peylin P, Brunke EG, Carouge C, Langenfelds RL, Lathiere J, Papa F, Ramonet M, Schmidt M, Steele LP, Tyler SC and White J (2006) Contribution of anthropogenic and natural sources to atmospheric methane variability. *Nature*, **443:** 439-443.

Bouwman AF (1990) Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. *In*: Bouwman AF (Ed.) Soils and the Greenhouse Effect. John Willy and Sons, New York. pp.61-192.

Bouwman AF (1991) Agronomic aspects of wetland rice cultivation and associated methane emissions. *Biogeochemistry*. **15**: 65-88.

Butterbach-Bahl K, Papen H and Rennenberg H (1997) Impact of gas transport through rice cultivars on methane emission from rice paddy fields. *Plant, Cell and Environment*, **20:** 1175-1183.

Butterbach-Bahl K, Papen H and Rennenberg H (2000) Scanning electron microscopy analysis of the aerenchyma in two rice cultivars. *Phyton*, **61**: 25-34.

Cai ZC, Xing H, Yan X, Xu H, Tsuruta HK, Yagi K and Minami K (1997) Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilizers and water management. *Plant and Soil*, **196:** 7-14.

Cai ZC and Mosier AR (2000) Effect of NH_4Cl addition on methane oxidation by paddy soils. *Soil Biology and Biochemistry*, **32**: 1537-1545.

Cai ZC and Mosier AR (2002) Restoration of methane oxidation abilities of desiccated paddy soils after re-watering. *Biology and Fertility of Soils*, **36:** 183-189.

Chanton JP, Whiting GJ, Blair NE, Lindau CW and Bollich PK (1997) Methane emission from rice: stable isotopes, diurnal variations, and CO_2 exchange. *Global Biogeochemical Cycles*, **11**: 15-27.

Cheng W, Yagi K, Sakai H and Kobayashi K (2006) Effects of elevated atmospheric CO_2 concentrations on CH_4 and N_2O emission from rice soil: an experiment in controlled-environment chambers. *Biogeochemistry*, **77:** 351-373.

Chin KJ and Conrad R (1995) Intermediary metabolism in methanogenic paddy soils and the influence of temperature. *FEMS Microbiology and Ecology*, **18:** 85-102.

Clark LH and Harris WH (1981) Observations on the root anatomy of rice (*Oryza sativa* L.). *American Journal of Botany*, **68:** 154-161.

Cohen JE (2003) Human population: The next half century. *Science*, **302:** 1172-1175.

Colmer TD, Gibberd MR, Wiengweera A and Tinh TK (1998) The barrier to radial oxygen loss from roots of rice (*Oryza sativa* L) is induced by growth in stagnant solution. *Journal of Experimental Botany*, **49:** 325.

Colmer TD (2003) Long-distance transport of gases in plants: a perspective on internal aeration and radial oxygen loss from roots. *Plant, Cell and Environment*, **26:** 17-36.

Conrad, R, Schutz H and Seiler W (1987) Emission of CH_4 from submerged rice fields into the atmosphere. *Atmospheric Chemistry*, **22:** 821-823.

Conrad R (1999) Soil microorganisms oxidizing atmospheric trace gases (CH_4, CO, H_2, NO). *Indian Journal of Microbiology*, **39:** 193-203.

Conrad R, Erkel C and Liesack W (2006) Rice cluster I methanogens, an important group of Archaea producing greenhouse gas in soil. *Current Opinion in Biotechnology*, **17:** 262-267.

Conrad R, Klose M, Noll M, Kemnitz D and Bodelier PLE (2008) Soil type links microbial colonization of rice roots to methane emission. *Global Change Biology*, **14:** 657-669.

Crutzen PJ (1991) Methane's sinks and sources. *Nature*, **350:** 380-381.

Crutzen PJ (1995) On the role of CH_4 in atmospheric chemistry: sources sinks and possible reductions in anthropogenic sources. *Ambio,* **24:** 52-55.

Dannenberg S and Conrad R (1999) Effect of rice plant on methane production and rhizospheric metabolism in paddy soil. *Biogeochemistry*, **45:** 53-71.

Debnath G, Jain MC, Kumar S, Sarkar K and Sinha SK (1996) Methane emission from rice fields amended with biogas slurry and farm yard manure. *Climate Change*, **5:** 1-13.

Denier Van der Gon HAC, Neue HU, Lantin RS, Wassmann R, Alberto MRC and Tan MJP (1992) Controlling factors of methane emissions from rice fields. *In*: WISM Workshop. Wageningen, Netherlands.

Denier Van der Gon HAC and Neue HU (1994) Impact of gypsum application on the methane emission from a wetland rice field. *Global Biogeochemical Cycle*, **8:** 127-134.

Denier Van der Gon HAC and Neue HU (1995) Influence of organic matter incorporation on the CH_4 emission from wetland rice field. *Global Biogeochemical Cycles*, **9:** 11-22.

Denier Van der Gon HAC and Neue HU (1996) Oxidation of methane in the rhizosphere of rice plants. *Biology and Fertility of Soils*, **22:** 359-366.

Denier Van der Gon HAC, Kropff MJ, Van Breemen N, Wassmann R, Lantin RS, Aduna E, Corton TM and Van Laar HH (2002) Optimizing grain yields reduces CH_4 emission from rice paddy fields. *Proceedings of National Academy of Science (USA),* **99:** 12021-12024.

Dubey SK (2001) Methane emission and rice agriculture. *Current Science*, **81:** 345- 346.

Dubey SK, Sinha ASK and Singh JS (2002) Differential inhibition of CH_4 oxidation in bare, bulk and rhizosphere soils of dryland rice field by nitrogen fertilizers. *Basic and Applied Ecology*, **3:** 347-355.

Dubey SK (2003) Spatio-kinetic variation of methane oxidizing bacteria in paddy soil at mid tillering: Effect of N fertilizer. *Nutrient Cycling in Agroecosystems*, **65:** 53-59.

Dubey, SK (2005) Microbial ecology of methane emission in rice agroecosystem: a review. *Applied Ecology and Environmental Research*, **3:** 1-27.

Dueck TA, Visser R de Poorter H, Persijn S, Gorissen A, Visser W de, Schapendonk A, Verhagen J, Snel J, Harren FJM, Ngai AKY, Francel VF, Bouwmeester H, Voesenek LACJ and Van der Werf A (2007) No evidence for substantial aerobic methane emission by terrestrial plants: a ^{13}C-labelling approach. *New Phytologist*, **175:** 29–35.

Evans JR (2007) Resolving methane fluxes. *New Phytologist*, **175:** 1-4.

Ferry JG (1997) Methane: small molecule, big impact. *Science*, **278:** 1413-1414.

Fetzer S, Bak F and Conrad R (1993) Sensitivity of methanogenic bacteria from paddy soils to oxygen and dessication. *FEMS Microbiology Ecology*, **12:** 107-115.

Frenzel P (2000) Plant-associated methane oxidation in rice fields and wetlands. *Advances in Microbial Ecology*, **16:** 85-114.

Garcia IL (1990) Taxonomy and ecology of methanogens. *FEMS Microbiological Review*, **87:** 297-308.

Ghosh S, Jain MC and Sinha SK (1995) Estimates of global methane production from rice paddies based on substrate requirement. *Current Science*, **69:** 937-939.

Gilbert B and Frenzel P (1998) Rice roots and CH_4 oxidation: the activity of bacteria, their distribution and the microenvironment. *Soil Biology and Biochemistry*, **30:** 1903-1916.

Gogoi N, Baruah KK, Gogoi B, Gupta PK and Das, KK. (2003) Physiological parameters of rice (*Oryza sativa* L.) associated with emission of methane from different agroecosystems. *Indian Journal of Plant Physiology*, Special Issue: 597-601.

Gogoi N, Baruah KK, Gogoi B and Gupta PK (2005) Methane emission characteristics and its relations with plant and soil parameters under irrigated rice ecosystem of northeast India. *Chemosphere*, **59:** 1677-1684.

Gogoi N, Baruah KK, and Gupta PK (2008) Selection of rice genotypes for lower methane emission. *Agronomy for sustainable development*, **28:** 181-186.

Gomez KA and Gomez AA (1984) Statistical Procedures for Agricultural Research. 2nd ed. John Wiley and Sons, New York, 680pp.

Goto E, Miyamori Y, Hasegawa S and Inatsu O (2004) Reduction effects of accelerating rice straw decomposition and water management on methane emission from paddy fields in a cold distinct. *Japanese Journal of Soil Science and Plant Nutrition*, **75:** 191-201.

Groot TT, Bodegom van PM, Meijer HAJ and Harren FJM (2005) Gas transport through the root–shoot transition zone of rice tillers. *Plant and Soil*, **277:** 107-116

Hansen J, Sato M, Ruedy R, Lo K, Lea DW and Medina-Elizade M (2006) Global temperature change. *The Proceedings of National Academy of Sciences (USA)*, **103:** 14288-14293.

Hanson RS and Hanson TE (1996) Methanotrophic bacteria. *Microbiology Review*, **62:** 439-471.

Hattori C, Ueki A, Seto T and Ueki K (2001) Seasonal variations in temperature dependence of methane production in paddy soil. *Microbes and Environments*, **16:** 227-233.

Henckel T, Friedrich M, Conrad R (1999) Molecular analysis of the methaneoxidizing microbial community in rice field soil by targeting the genes of the 16S rRNA, particulate methane monooxygenase, and methanol dehydrogenase. *Applied and Environmental Microbiology*, **65:** 1980-1990.

Hogan KB, Hoffman JS, Thompson AM (1991) Methane on the greenhouse agenda. *Nature*, **354:** 181-182.

Holzapfel-Pschorn A, Conrad R and Seiler W (1986) Production, oxidation and emission of methane in rice paddies. *FEMS Microbiology Ecology*, **31:** 149-158.

Hori K, Inubushi K, Matsumoto S and Wada H (1993) Competition for hydrogen between methane formation and sulfate reduction in a paddy soil. *Japanese Journal of Soil Science and Plant Nutrition*, **64:** 363-367.

Hori T, Noll M, Igarashi Y, Friedrich MW and Conrad R (2007) Identification of acetate-assimilating microorganisms under methanogenic conditions in anoxic rice field soil by comparative stable isotope probing of RNA. *Applied and Environmental Microbiology*, **73:** 101-109.

Hosono T and Nouchi I (1997) The dependence of methane transport in rice plants on the root zone temperature. *Plant and Soil*, **191:** 233-240.

Houghton JT, Filho LG, Bruce J, Lee H, Callander BA, Haites E, Harris N and Maskell K (1995) Climate change 1994. Cambridge University Press, London, UK.

Huang Y, Sass RL and Fisher FM (2002) Methane emission from Texas rice paddy soils. 2. Seasonal contribution of rice biomass production to CH_4 emission. *Global Change Biology*, **3:** 491-500.

Hutsch BW, Webster CP and Powlson DS (1994) Methane oxidation in soil as affected by land use, pH, and N-fertilization. *Soil Biology and Biochemistry*, **26:** 1613- 1622.

International Panel on Climate Change (IPCC) (1992) Climate Change 1992, the supplementary reports to the IPCC scientific assessment. Houghton JT, Callander BA and Varney SK (eds) Cambridge University Press, Cambridge, UK.

IPCC (2007) Solomon, S, Qin D, Manning M, Alley RB, Berntsen T, Bindoff NL, Chen Z, Chidthaisong A, Gregory JM, Hegerl GC, Heimann M, Hewitson B, Hoskins BJ, Joos F, Jouzel J, Kattsov V, Lohmann U, Matsuno T, Molina M, Nicholls N, Overpeck J, Raga G, Ramaswamy V, Ren J, Rusticucci M, Somerville R, Stocker TF, Whetton P, Wood RA and Wratt D (2007) Technical Summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor

and H.L. Miller (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IRRI (1989) Toward 2000 and Beyond, The International Rice Institute, Manila, Philippines.

Ishermann K (1994) Agriculture's share in emission of trace gases affecting the climate and some cause-oriented proposals for sufficiently reducing this share. *Environmental Pollution*, **83:** 95-111.

Jackel U, Schnell S and Conrad R (2001) Effects of moisture, texture and aggregate size of paddy soil on production and consumption of CH_4. *Soil Biology and Biochemistry*, **33:** 965-971.

Jackson ML (1973) Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd. New Delhi.

Jackson M and Armstrong W (1999) Formation of aerenchyma and the processes of plant ventilation in relation to soil flooding and submergence. *Plant Biology*, **1:** 274-287.

Jain MC, Kumar S, Wassmann R, Mitra S, Singh SD, Singh JP, Singh R, Yadav AK and Gupta S (2000) Methane emissions from irrigated rice fields in Northern India (New Delhi). *Nutrient Cycling in Agroecosystems*, **58:** 75-83.

Jermasawatdipong P, Murase I, Prabuddham P, Hasathon Y, Khomthong N, Naklang K, Watanabe A, Haaraguchi H and Kimura K (1994) Methane emission from plots with differences in fertilizer application in Thai paddy fields. *Soil Science and Plant Nutrition*, **40:** 63-71.

Jia ZJ, Cai ZC, Xu H and Tsuruta H (2002) Effects of rice cultivars on methane fluxes in a paddy soil. *Nutrient Cycling in Agroecosystems*, **64:** 87-94.

Jimenez, J and Lal R (2006) Mechanism of sequestration in soils of Latin America. *Critical Review in Plant Science*, **25:** 337-365.

Jones WJ (1991) Diversity and physiology of methanogens, *In:* Rogers, JR, Whitman WB (Eds.) Microbial Production and Consumption of Greenhouse Gas: CH_4, nitrogen oxides, and halo methane American Society for Microbiology, Washington, DC. p 39-56.

Joos F and Spahni R (2008) Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. *The Proceedings of National Academy of Sciences (USA),* **105:** 1425-1430.

Joulian C, Escoffier S, Lemer J, Neue HU, Roger PA (1997) Population and potential activities of methanogens and methanotrophs in rice fields: Relation with soil properties. *European Journal of Soil Biology,* 33: 105-166.

Joulian C, Ollivier B, Patel BKC, Roger PA (1998) Phenotypic and phylogenetic characterization of dominant culturable methanogens isolated from rice fields soils *FEMS Microbiology Ecology,* 25: 135-145.

Keppler F, Hamilton JTG, Brab M and Rockmann T (2006) Methane emissions from terrestrial plants under aerobic conditions. *Nature*, **439:** 187-191.

Keppler F and Rockmann T (2007) Methane, plants and climate change. *Scientific American,* **296:** 40-45.

Kesheng S, Zhen L (1997) Effect of rice cultivars and fertilizer management on methane emission in a rice paddy in Beijing. *Nutrient Cycling in Agroecosystems,* **49**: 139-146.

Khalil MAK and Rasmussen RA (1990) Constraints on the global sources of methane and an analysis on recent budgets. *Tellus B*, **42**: 229-236.

Khalil MAK (1999) Non-CO_2 greenhouse gases in the atmosphere. *Annual Review of Energy and the Environment,* **24:** 645-61.

Kimura M, Miura Y, Watanabe A, Katoh T and Haraguehi H (1991) Methane emission from paddy field. (I) effect of fertilization, growth stage and midsummer drainage. pot experiment. *Environmental Science*, **14:** 265-271.

King GM (1992) Ecological aspect of methane oxidation, a key determinant of global methane dynamics. *In:* Mashall KC (Ed.) Advances in Microbial Ecology. Plenum, New York. pp. 431-468.

Kludze HK, Delaune RD and Patrick Jr WH (1993) Aerenchyma formation and methane and oxygen exchange in rice. *Soil Science Society of Ammerica Journal*, **57:** 386-391

Kongchum M, Bollich PK, Hudnall WH, DeLaune RD and Lindau CW (2006) Decreasing methane emission of rice by better crop management. *Agronomy for Sustainable Development*, **26:** 45-54.

Krik GJD, Santos EE and Santos MB (1999) Phosphate solubilization by organic anion excretion from rice growing in aerobic soil: rates of excretion and decomposition, effects on rhizosphere and pH and effects on phosphate solubility and uptake. *New Phytologist*, **135**: 191-200.

Kruger M, Frenzel P and Conrad R (2001) Microbial processes influencing methane emission from rice fields. *Global Change Biology*, **7:** 49-63.

Kudo Y, Nakojima T, Miyaki T and Oyaizu H (1997) Methanogen flora of paddy soils in Japan. *FEMS Microbiology Ecology*, **22:** 39-48.

Kumaraswamy S, Rath AK, Ramakrishnan B and Sethunathan N (2000) Wetland rice soils as sources and sinks of methane: a review and prospects for research. *Biology and Fertility of Soils*. **31:** 449-461.

Ladha JK, Tirol AC, Darby LG, Caldo G, Ventura W and Watanabe L (1986) Plant associated N_2 fixation (C_2H_2 reduction) by five rice varieties and relationship with plants growth characters as affected by straw application. *Soil Science and Plant Nutrition*, **32:** 1962-1972.

Le M, Escoffier S, Chessel C and Roger AA (1996) Microbial aspects of methane emission in rice field soil from Camargue (France): 2. Methanotrophy and related microflora. *European Journal of Soil Biology*, **32:** 71-80.

Lehmann-Richter S, Grosskopf R, Liesack W, Frenzel P and Conrad R (1999) Methanogenic archaea and CO_2 dependent methanogenesis on washed rice roots. *Environmental Microbiology*, **1:** 159-166.

Lelieveld J, Crutzen PJ and Brühl C (1993) Climate effects of atmospheric methane. *Chemosphere*, **26:** 739-768.

Lin EH, Dong H and Li Y (1995) Methane emissions of China; Agricultural sources and mitigation options. *In:* Agricultural Sources and Mitigation Options, Proc Symp Non-CO_2 Greenhouse Gases. Kluwer Academic Publishers, The Netherlands.

Lindau CW, Alford DP, Bollich PK and Linscombe SD (1993) Inhibition of methane evolution by calcium sulfate addition to flooded rice. *Plant and Soil*, **158**: 299-301.

Lindau CW (1994) Methane emission from Louisiana rice fields amended with nitrogen fertilizers. *Soil Biology and Biochemistry*, **26:** 353-359.

Lu Y, Wassmann R, Neue HU and Huang C (2000) Dynamics of dissolved organic carbon and methane emissions in a flooded rice soil *Soil Science Society of American Journal*, **64:** 2011-2017.

Lu Y, Watanabe A and Kimura M (2002) Input and distribution of photosynthesized carbon in a flooded rice soil. *Global Biochemical Cycle*, **16:** 1085.

Ludmila C, Julia A, Rudoyk R, Toms M and Lidstrom E (1998) G Transfer enzymes and coenzymes linking methylotrophic bacteria and methanogenic archea. *Science*, **281:** 99-101.

Lynch JM and Whipps JM (1990) Substrate flow in the rhizosphere. *Plant and Soil*, **129:** 1-10.

Maclean JL, Dawe DC, Hardy B and Hettel GP (2002) Rice Almanac. International Rice Research Institute, Los Banos, Philippines.

Mancinelli RL, White MR and Bogher I (1991) Microbial methane oxidation. *In:* Wilkey PL (Ed.) Rio vista gas leak study, Argonne National Laboratory Topical Report, April 1989 to January 1991 Argonne National Laboratory IL.

Mancinelli RL (1995) The regulation of methane oxidation in soil. *Annual Review of Microbiology*, **49:** 581-605.

Mariko S, Harazono YN and Nouchi I (1991) Methane in flooded soil, water and the emission through rice plants to the atmosphere. *Environmental and Experimental Botany*, **31:** 343-350.

Marschner H (1996) Mineral Nutrition of Higher Plants. Academic Press, London.

Masscheleyn PH, Delaune RD and Patrick WH (1993) Methane and nitrous oxide emission from laboratory measurements of rice soil suspension: Effect of soil oxidation-reduction status. *Chemosphere*, **26:** 251-260.

Matthews E, Fung I and Lerner J (1991) Methane emission from rice cultivation: geographic and seasonal distribution of cultivated areas and emissions, *Global Biogeochemical Cycles*, **5:** 3-24.

Mattson MD and Likens GE (1990) Air pressure and CH_4 fluxes. *Nature*, **347:** 718-719.

Minami K, Goudrian J, Lantinga EA, Kimura T (1993) Significance of grasslands in emission and absorption of greenhouse gases. *In:* Proceedings of 17th International Grassland Congress. pp. 1231-1238.

Minami K (1994) Methane from rice production. *Fertilizer Research*, **37:** 167-180.

Minami K and Neue HU (1994) Rice paddies as a methane source. *Climatic Change*, **27**: 13-26.

Minami K, Mosier A and Sass R (1994) CH_4 and N_2O: Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources. NIAES Series 2. Yokendo Publishers, Tokyo, Japan.

Minami K (1997) Atmospheric methane and nitrous oxide: sources, sinks and strategies for reducing agricultural emissions. *Nutrient Cycling in Agroecosystems*, **49:** 203-211.

Minamikawa K and Sakai N (2005) The effect of water management based on soil redox potential on methane emission from two kinds of paddy soils in Japan. *Agriculture, Ecosystems and Environment*, **107:** 397-407.

Minamikawa K and Sakai N (2006) The practical use of water management based on soil redox potential for decreasing methane emission from a paddy field in Japan *Agriculture, Ecosystems and Environment*, **116:** 181-188.

Minamikawa K, Sakai N and Yagi K (2006) Methane emission from paddy fields and its mitigation option on a field scale. *Microbes Environment*, **2:** 135-147.

Minoda T and Kimura M (1994) Contribution of photosynthesized carbon to the methane emitted from paddy fields. *Geophysics Research Letter*, **21:** 2007-2010.

Mishra S, Rath AK, Adhya TK, Rao VR and Sethunathan N (1997) Effect of continuous and alternate water regimes on methane flux from rice under greenhouse conditions. *Biology and Fertility of Soils*, **24:** 399-405.

Mitra S, Aulakh MS, Wassmann R and Olk DC (2005) Triggering of methane production in rice soils by root exudates: effects of soil properties and crop Management. *Soil Science Society of American Journal*, **69:** 563-570.

Naser HM, Nagata O, Tamura S and Hatano R (2007) Methane emission from five paddy with different amounts of rice straw application in Hokkaido, Japan. *Soil Science and Nutrition*, 53: 95-101.

Nayak DR, Babu YJ, Datta A and Adhya TK (2007) Methane oxidation in an intensively cropped tropical rice field soil under long-term application of organic and mineral fertilizers. *Journal of Environmental Quality*, **36:** 1577-1584.

Neinhuis C and Edelmann HG (1996) Methanol as a rapid fixative for the investigation of plant surfaces by SEM. Journal of Microscopy, **184:** 14-16.

Neue HU (1993) Methane emission from rice fields. *Biosciences*, **43:** 466-474.

Neue HU and Roger PA (1993) Rice agriculture: factors controlling emissions. *In:* Khalil MAK (Ed.) Atmospheric Methane: Sources, Sinks and Role in Global Change. Springer-Verlag, Berlin, pp. 254-298.

Neue HU, Wassmann R, Lantin RS, Alberto MCR and Aduna JB (1994) Methane emission from rice fields. *IRRN Research Notes*, **19:** 3-31.

Neue HU, Wassmann R and Lantin RS (1995) Mitigation options for methane emission from rice-fields. *In*: Peng S, Ingarm KT, Neue, HU and Ziska LH Eds. Climate Change and Rice, Springer-Verlag, Berlin, Heidelberg, pp. 136-144.

Neue HU, Wassmann R, Lantin RS, Alberto MCR, Aduna JB and Javellana AM (1996) Factors affecting methane emission from rice fields. *Atmospheric Environment*, **30:** 1751-1754.

Neue HU, Wassmann R, Kludze HK, Bujun W and Lantin RS (1997) Factors and processes controlling methane emissions from rice fields. *Nutrient Cycling in Agroecosystems*, **49:** 111-117.

Neue HU and Roger PA (2000) Rice agriculture: factors controlling emission. *In:* Ed. Khalil MAK Atmospheric Methane, Springer, Berlin. pp.134-169.

Nouchi I, Mariko S and Aoki K (1990) Mechanism of methane transport from the rhizosphere to atmosphere through rice plants. *Plant Physiology*, **94:** 59-66.

Nouchi I and Mariko S (1993) Mechanism of methane transport by rice plants. *In:* Oremland RS (Ed.) Biogeochemistry of Global Change: Radiatively Active Trace Gases. pp. 336-352.

Nouchi I (1994) Mechanisms of methane transport through rice plants. *In*: Minami K, Mosier A and Sass RL (Eds.) CH_4 and N_2O: Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources NIAES Series 2, Tsukuba, Japan, pp. 87-104.

Nouchi I, Hosono T, Aoki K and Minami K (1994) Seasonal variation in CH_4 flux from rice paddies associated with CH_4 concentration in soil water, rice biomass and temperature and its modeling. *Plant and Soil*, **161:** 195-208.

Palmer RR and Reeve IN (1993) Methanogene genes and the molecular biology of methane biosynthesis. *In:* Sebald M (ed.) Genetics and Molecular Biology of Anaerobic Bacteria. Springer-Verlag, Berlin. pp. 13-35.

Papen H and Rennenberg H (1990) Microbial processes involved in the emission of radio actively important trace gases. *In:* Transactions of 14th International Soil Science Congres. **2**: 232-237, Kyoto, Japan.

Parashar D, Rai CJ, Gupta PK and Singh N (1991) Parameters affecting methane emission from rice paddies. *Indian Journal of Radio and Space Physics,* **20:** 12-17.

Parashar DC, Mitra AP, Gupta PK, Rai J, Sharma RC, Singh N, Kaul S, Lal G, Chaudhary A, Ray HS, Das SN, Parida KM, Rao SB, Swamy SP, Singh G, Gupta SK, Singh AR, Banerjee R, Sethunathan N, Adhya TK, Rao VR, Palit P, Saha AK, Purkait NN, Chaturvedi GS, Sen SP, Sen M, Sarkar B, Banik A, Subbaraya BH, Lal S, Venkatramani and Sinha SK (1994) Methane budget from paddy fields in India. *Current Science*, **66:** 938-940.

Parashar DC, Mitra AP, Sinha SK, Gupta PK, Rai J, Sharma RC, Singh N, Kaul S, Lal G, Chaudhary A , Ray HS, Das SN, Parida KM, Rao SB, Kanung SP, Ramasami T, Nair BU, Swamy M, Singh G, Gupta SK, Singh AR, Saikia BK, Barua AKS, Pathak MG, Lyer CPS, Gopalakrishnan M, Sane PV, Singh SN, Banerjee R, Sethunathan N, Adhya TK, RaoVR, Palit P, Saha AK, Purkait NN, Chaturvedi GS, Sen SP, Sen M, Sarkar B, Banik A, Subbaraya BH, Lal S and Venkatramani S (1994a) Methane budget from Indian paddy fields. *In:* Minami K, Mosier A and Sass RL (Eds.) CH_4 and N_2O: Global Emissions and Controls From Rice Fields and Other Agricultural and Industrial Sources. NIAES Series 2, Tsukuba, Japan, pp.27-39.

Parashar DC, Mitra AP, Gupta PK, Rai J, Sharma RC, Singh N, Koul S, Ray HS, Das S N, Parida KM, Rao SB, Kanungo SP, Ramasami T, Nair BU, Swamy M, Singh G, Gupta SK, Singh AR, Saikia BK, Barua AKS, Pathak, MG, Iyre CSP, Gopalakrishnan M, Sane PV, Singh SN, Banerjee R, Sethunathan N, Adhya TK, Rao VR, Palit P, Saha AK , Purkait NN, Chaturvedi GS, Sen SP, Sen M, Sarkar B, Banik A and Sinha SK (1996) Methane budget from paddy fields in India. *Chemosphere* **33**: 737-757.

Pathak H, Li C and Wassmann R (2005) Greenhouse gas emissions from Indian rice fields: calibration and upscaling using the DNDC model. *Biogeosciences*, **2:** 113-123.

Patrick WH Jr (1981) The role of inorganic redox systems in controlling reduction in paddy soils. *In:* Proceedings of Symposium on Paddy Soil. Institute of Soil Science, Academia Sinica. Beijing and Springer Verlag, Berlin. pp. 107-117.

Ponnamperuma FN. (1972) The chemistry of submerged soils. *Advances in Agronomy*, **24:** 29-96.

Rajgopal BS, Belay N and Daniel L (1988) Isolation and characterization of methanogenic bacteria from rice paddies. *FEMS Microbiology Ecology*, **53:** 153-158.

Ramakrishnan B, Satpathy SN, Patnaik P, Adhya TK, Rao VR and Sethunathan N (1995) Methane production in two Indian rice soils. *Geomicrobiology Journal*, **13:** 193-199.

Rath AK, Mohanty SR, Mishra S, Kumaraswamy S, Ramakrishnan B and Sethunathan N (1999) Methane production in unamended and rice-straw amended soil at different moisture levels. *Biology and Fertility of Soils*, **28:** 145-149.

Rath AK, Swain B, Ramakrishnan B, Panda D, Adhya TK, Rao, VR and Sethunathan N (1999a) Influence of fertilizer management and water regime on methane emission from rice fields. *Agriculture Ecosystems and Environment*, **76:** 99-107.

Reeburgh WS, Whjalen SC and Alperin MJ (1993) The role of methylotrophy in the global methane budget *In:* Murrell JC and Kelly DP (Eds.) Microbial growth on CI compound. Intercept Ltd., Andover, D.K. pp.1-14.

Reichardt W, Mascarina G, Padre B and Doll J (1997) Microbial communities of continuously cropped, irrigated rice fields. *Applied and Environmental Microbiology*, **63:** 233-238.

Rothfuss F and Conrad R (1993) Development of gas diffusion probe for the determination of methane concentrations and diffusion characteristics in flooded paddy soil. *FEMS Microbiology Ecology*, **15:** 883-886.

Sakai S, Imachi H, Sekiguchi Y, Ohashi A, Harada H and Kamagata Y (2007) Isolation of key methanogens for global methane emission from rice paddy fields: a novel isolate affiliated with the clone cluster rice cluster I. *Applied and Environmental Microbiology*, **73:** 4326-4331.

Sass RL, Fisher FM, Harcombe PA and Turner FT (1990) Methane production and emission in a Texas rice field. *Global Biogeochemical Cycles*, **4:** 47-68.

Sass RL, Fisher FM, Harcombe PA and Turner FT (1991) Mitigation of methane emission from rice fields: effect of incorporated rice straw. *Global Biogeochemical Cycles*, **5:** 275-288.

Sass RL and Fisher FM (1992) CH_4 emission from paddy fields in the United State gulf coast area. *In:* Minami K, Mosier A and Sass RL (Eds) CH_4 and N_2O Global Emissions and Controls from Rice-fields and other Agricultural and Industrial Sources. NIAES Ser. 2. pp. 65-78.

Sass RL, Fisher FM and Wang YB (1992) Methane emission from rice fields: The effect of floodwater management. *Global Biogeochemical Cycles*, **6:** 249-262.

Sass RL and Fisher Jr FM (1994) CH_4 emission from paddy fields in the United States gulf coast area. *In:* Minami CK, Mosier A, Sass RL (eds.) CH_4 and N_2O: Global Emissions and Controls from Rice Fields and other Agricultural and Industrial Sources. NIAES Series 2, Tsukuba, Japan. pp. 65- 77.

Sass RL and Cicerone RJ (2002) Photosynthate allocation in rice plants: Food production or atmospheric methane. *Proceedings of National Academy of Science (USA)*, **99:** 11993-11995.

Sass RL, Mosier A and Zheng XH (2002) Introduction and summary: International Workshop on Greenhouse Gas Emissions from Rice Fields in Asia. *Nutrient Cycling in Agroecosystems*, **64:** ix –xv.

Satpathy SN, Rath AK, Ramakrishnan B, Rao VR, Adhya TK and Sethunathan N (1997) Diurnal variation in methane efflux at different growth stages of tropical rice. *Plant and Soil.* **195:** 267-271.

Satpathy, SN, Mishra S, Adhya TK, Ramakrishnan B, Rao VR and Sethunathan N (1998) Cultivar variation in methane efflux from tropical rice. *Plant Soil*, **202:** 223-229.

Scheehle EA and Kruger D (2006) Global anthropogenic methane and nitrous oxide emissions. *Energy Journal*, **3:** 33-44.

Schimel J (2000) Rice, microbes and methane. *Nature*, **403:** 375-377.

Schutz H, Holzaptel-Pschorn A, Conrad R, Rennenberg H and Seiler W (1989) A three-year continuous record on the influence of day time season and fertilizer treatment on methane emission rates from an Italian rice paddy. *Journal of Geophysics Research,* **94:** 16405-16416.

Sebacher DT, Hams RC and Bartlett KB (1983) Methane flux across the air water interface: air velocity effects. *Tellus*, **35:** 1-10.

Seiler W, Holzapfel-Pschorn A, Conrad R and Scharffe D (1984) Methane emission from rice paddies. *Journal of Atmospheric Chemistry*, **1:** 241-268.

Setyanto P, Makarim K, Fagi, AM, Wassmann R and Buendia LV (2000) Crop management affecting methane emissions from irrigated and rainfed rice in central Java, Indonesia. *Nutrient Cycling in Agroecosystems,* **58:** 31-42.

Sharma AR, Moorthy BTS, Rao KS and Venkateswarlu B (1995) Improvement of rice production technology in the conventional areas of eastern India. *In:* Deb DL (Ed.) Sustaining Crop and Animal Productivity -The Challenge of the Decade. Associated Publishing Co., New Delhi, pp. 157-178.

Shima SL (1998) Mechanism of biological methane formation: Structure and function of methyl-coenzyme M. reductase. *Protein, Nucleic Acid and Enzyme*, **43:** 1461-1467.

Shine KP, Fouquart Y, Ramaswamy V, Solomon S and Srinivasan J (1995) Radiative forcing. *In:* J.T. Houghton JTM *et al* (Eds) Climate Change 1994: Radiative forcing

of climate change and an evaluation of the IPCC IS92 emission scenarios. Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge. pp. 163-203.

Singh S, Singh JS and Kashyap AK (1999) Methane flux from irrigated rice fields in relation to crop growth and N-fertilization. *Soil Biology and Biochemistry*, **31:** 1219-1228.

Singh SN, Verma A and Tyagi L (2003) Biogenic emission of GHGs from agricultural fields. *Physiology and Molecular Biology of Plants*, **9:** 63-73.

Sinha SK (1995) Global methane emission from rice paddies: Excellent methodology but poor extrapolation. *Current Science*, **68:** 643-646.

Thurlow M, Karda KI, Tsurula H and Minami K (1995) Methane uptake by unflooded paddy soils: The influence of soil temperature and atmospheric methane concentration. *Soil Science and Plant Nutrition*, **41:** 371-375.

Topp E and Pattey E (1997) Soil as a source and sinks for atmospheric methane. *Canadian Journal of Soil Science*, **77:** 167-178.

Trotsenko YA and Khmelenina VN (2002) Biology of extremophilic and extremotolerant methanotrophs. *Archives of Microbiology*, **177:** 123-131.

Tsutsuki K and Ponnamperuma FN (1987) Behavior of anaerobic decomposition products in submerged soils: Effect of organic amendment, soil properties and temperature. *Soil Sciience and Plant Nutrition,* **33**: 13-33.

USEPA (United States-Environmental Protection Agency) (2006) Overview of methane's contribution to global warming. *In:* Methane Emissions and Opportunities for Control, US-EPA/Air and Radiation, Washington, pp. 2-24.

Verburg PH, Bodegom PM, Denier Van der Gon, HAC, Bergsma A, Van Breemen NO (2006) Upscaling regional emissions of greenhouse gases from rice cultivation: methods and sources of uncertainty. *Plant Ecology*, **182:** 89-106.

Vogel DD, Keltjens JT and Vander DC (1988) Biochemistry of methane production. *In*: Zehnder AJB (ed) Biology of Anaerobic Microorganisms. Wiley. New York. pp 707-770.

Wang B, Neue HU and Samonte HP (1997) Role of rice in mediating methane emission. *Plant and Soil*, **189:** 107-115.

Wang B, Neue HU and Samonte HP (1997a) Effect of cultivar difference ('IR 72', 'IR 65598' and 'Dular') on methane emission. *Agriculture, Ecosystems and Environment*, **62:** 31-40.

Wang B, Xu Y, Wang Z, Li Z, Guo Y, Shao K and Chen Z (1999) Methane emission from rice fields as affected by organic amendment, water regime, crop establishment and rice cultivar. *Environmental Monitoring and Assessment*, **57:** 213-228.

Wang B and Adachi K (2000) Differences among rice cultivars in root exudation, methane oxidation, and populations of methanogenic and methanotrophic bacteria in relation to methane emission. *Nutrient Cycling in Agroecosystems*. **58:** 349-356.

Wang MX, Dai A, Shangguan X, Ren L, Shen R, Schuts H, Seiler W, Rasmussen RA and Khalil MAK (1994) Source of methane in China. *In:* Minami K, Mosier A and Sass R (Eds) CH_4 and N_2O: Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources. NIAES Series 2, Yokendo Publishers, Tokyo, Japan. pp 9-26.

Wang ZP, Lindau CW, Delaune RD and Patrick WH Jr (1992) Methane production from anaerobic soil amended with rice straw and nitrogen fertilizers. *Fertilizer Research*, **33:** 115-121.

Wang ZP, Lindau CW, delaune RD and Patrick Jr WH (1993) Methane emission and entrapment in flooded rice soils as affected by soil properties. *Biology and Fertility of Soils*, **16:** 160-168.

Wang ZP, Delaune RD, Masscheleyn PB and Patrick Jr. WH (1993a) Soil redox and pH effects on methane production in a flooded rice soils. *Soil Science Society of American Journal,* **57:** 382-385.

Wang ZP, Zeng D and Patrick Jr. WH (1997b) Characteristics of CH_4 oxidation in a flooded rice profile. *Nutrient Cycling in Agroecosystems,* **49:** 97-103.

Wassmann R, Papen H and Rennenberg H (1993) Methane emission from rice paddies and possible mitigation options. *Chemosphere,* **26:** 201-217.

Wassmann R, Neue HU, Lantin RL, Aduna JB, Alberto MC, Andales MJ, Tan MJ, Denier Van der Gon HAC, Hoffmann H, Papen H, Rennenberg H and Seiler W (1994) Temporal patterns of methane emissions from wetland rice fields treated by different modes of N application. *Journal of Geophysical Research,* **99:** 16457-16462.

Wassmann R, Shangguan XJ, Tolg M, Cheng DX, Wang MX, Papen H, Rennenberg H and Seiler W (1996) Spatial and seasonal distribution of organic amendments affecting methane emission from Chinese rice fields. *Biology and Fertility of Soils,* **22:** 191-195.

Wassmann R and Martius CS (1997) Methane emission from the Amazon flood plain. *In:* Junk, WJ (Ed.) The Central Amazon floodplain: Ecological Studies 126. Springer-Verlag, Berlin. pp. 137-143.

Wassmann R, Neue HD, Bueno C, Latin RS, Alberto MCR, Buendia LV, Bronson K, Papen H and Rennenberg H (1998) Methane production capacities of different rice soils derived from inherent and exogenous substrates. *Plant and Soil,* **203:** 227-237.

Wassmann R, Buendia LV and Lantin RS (2000) Mechanisms of crop management impact on methane emissions from rice fields in Los Banos, Philippines. *Nutrient Cycling in Agroecosystems,* **58:** 107-119.

Wassmann R, Lantin RS, Neue HD, Buendia LV, Corton TM and Lu Y (2000a) Characterization of methane emissions from rice fields in Asia. III Mitigation options and future research needs. *Nutrient Cycling in Agroecosystems,* **58:** 23-36.

Wassmann R and Dobermann A (2008) Greenhouse gas emission from rice fields: mechanisms, experiments and mitigation options. *In:* Aggarwal *et al.* (Eds.) Science, Technology, and Trade for Peace and Prosperity. IRRI / Macmillan, India. pp. 449-458.

Watanabe A and Kimura M (1995) Methane production and its fate in paddy fields. VIII Seasonal variation in the amount of CH_4 retained in soil. *Soil Science and Plant Nutrition*, **41:** 225-233.

Watanabe D, Hashmoto T and Shimoyama A (1997) Methane oxidizing activities and methanotrophic population associated with wetland rice plants. *Biology and Fertility of Soils*, **24:** 261-265.

Weiguo C, Kazuyuki Y, Hidemitsu S and Kazuhiko K (2006) Effects of elevated atmospheric CO_2 concentration on CH_4 and N_2O emission from rice soil: An experiment in controlled-environment chambers. *Biogeochemistry*, **77:** 351-373.

Whalen SL, Reelourgh WS and Sandbes KA (1990) Rapid methane oxidation in a landfill cover soil. *Applied and Environmental Microbiology*, **6:** 3405-3411.

Wilbanks TJ and Kates RW (1999) Global changes in local places: How scale matters. *Climatic Change*, **43:** 601-628.

Xu H, Cai ZC, Jia ZJ and Tsuruta H (2000) Effect of land management in winter crop season on CH_4 emission during the following flooded and rice growing period. *Nutrient Cycling in Agroecosystems*, **58:** 12-18.

Yagi K and Minami K (1990) Effects of organic matter application on methane emission from some Japanese paddy fields. *Soil Science and Plant Nutrition*, **36:** 599-610.

Yagi K, Tsuruta H and Minami K (1997) Possible options for mitigating methane emission from rice cultivation. *Nutrient Cycling in Agroecosystems*, **49:** 213-220.

Yan X, Yagi K, Akiyama H and Akimoto H (2005) Statistical analysis of the major variables controlling methane emission from rice fields. *Global Change Biology*, **11:** 1131-1141.

Yao H and Conrad R (1999) Thermodynamics of methane production in different rice paddy soils from China, the Philippines and Italy. *Soil Biology and Biochemistry*, **31:** 463-473.

Yao H, Conrad R, Wassmann R and Neue HD (1999) Effect of soil characteristic on sequential reduction and methane production in sixteen rice paddy soils from China, the Phillipines, Italy. *Biogeochemistry*, **47:** 269-295.

Yao H, Yagi K and Nouchi I (2000) Importance of physical plant properties on methane transport through several rice cultivars. *Plant and Soil*, **222:** 83-93.

Yao, H and Conrad, R (2001) Thermodynamics of propionate degradation in anoxic paddy soil from different rice-growing regions. *Soil Biology and Biochemistry*, **33:** 359-364.

Zhongjun J, Zucong C and Haruo T (2006) Effect of rice cultivar on CH_4 production potential of rice soil and CH_4 emission in a pot experiment. *Soil Science and Plant Nutrition*, **52:** 341-348.

Zou J, Huang Y, Jiang J, Zheng X and Sass RL (2005) A 3-year field measurement of methane and nitrous oxide emission from rice paddies in China: Effects of water regime, crop residue and fertilizer application. *Global Biogeochemical Cycles*, **19:** 2021.

APPENDIX

List of Publications

1. Das Kaushik and Baruah KK. (2008) A comparison of growth and photosynthetic characteristics of two improved rice cultivars on methane emission from rainfed agroecosystem of northeast India. *Agriculture, Ecosystems and Environment* (Elsevier), **124:** 105–113
2. Das Kaushik and Baruah KK (2008) Association between contrasting methane emissions of two rice (*Oryza sativa* L.) cultivars from the irrigated agroecosystem of northeast India and their growth and photosynthetic characteristics. *Acta Physiologiae Plantarum* (Springer), **30:** 569-578
3. Das Kaushik and Baruah KK (2008) Methane emission associated with anatomical and morphophysiological characteristics of rice (*Oryza sativa* L.) plant. *Physiologia Plantarum* (Blackwell) (in the press)

Communicated Papers

1. Das Kaushik, Baruah, KK and Gogoi N (2008) Growth and photosynthetic characteristics of rice (*Oryza sativa* L.) plant associated with methane emission from monsoon paddy agroecosystem
2. Baruah KK and Das Kaushik (2008) Methane emission from wetland agroecosystem of subtropical humid condition of India

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A comparison of growth and photosynthetic characteristics of two improved rice cultivars on methane emission from rainfed agroecosystem of northeast India

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Abstract

Wetland rice fields serve as an important anthropogenic source of atmospheric methane, a greenhouse gas implicated in global warming An experiment was conducted at the North Bank Plain Zone of Assam, India, during summer rice growing season (April–July 2006) in order to elucidate the effects of morpho-physiological characteristics of rice (*Oryza sativa* L) plants on methane emission from paddy fields Two improved rice cultivars *viz* Disang and Luit were grown in light textured loamy soil (Sand 28 50%, Clay 30 10%, Silt 41 40%, electrical conductivity (EC) 0 43 mmhos/100 g, cation exchange capacity (CEC) 10 20 meq 100 g^{-1}) under rainfed condition Higher seasonal integrated methane flux was recorded in cultivar Disang (E_{sif} = 1 38 g m^{-2}) compared to Luit (E_{sif} = 0 96 g m^{-2}) Both the cultivars exhibited two emission peaks, one at active vegetative growth stage and the other at panicle initiation stage of the crop Methane emission from the cultivars was significantly regulated by crop phenology and growth Vegetative growth in terms of leaf number and area, root volume and length and tiller number was higher in Disang Statistical analysis of these parameters showed a positive correlation with methane emission On the other hand, yield and all yield-attributing parameters were found to be superior in cultivar Luit Cultivar Luit recorded higher photosynthetic rate after panicle initiation On the other hand, Disang recorded higher rate of photosynthesis during active vegetative growth period In Luit, maximum partitioning of photosynthates was found towards the developing panicle, whereas in cultivar Disang, photosynthates could not be allocated sufficiently towards the panicle In Disang, maximum partitioning of photosynthates was recorded towards the vegetative parts (including root) of the rice plant Variation in organic carbon content of soil was observed in the field planted with two cultivars Higher soil organic carbon content was recorded in the field planted with cultivar Disang From this, we hypothesize that in Disang, photosynthetic carbon products were utilized as substrate by methanogens in the rhizosphere leading to more production of methane Additionally, higher vegetative growth with high methane transport capacity (MTC) may positively contribute to higher methane emission from cultivar Disang
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Keywords Growth, Methane, Organic carbon, Phenology, Photosynthesis, Rice

1. Introduction

Methane is an important greenhouse gas and its atmospheric concentration has almost tripled since pre-industrial times (Lelieveld et al , 1998) Methane influences the photochemistry of the atmosphere, accounts for about 15% of the current increase in global warming (Batjes and Bridges, 1992) Although, methane can be emitted from plants under aerobic condition (Keppler et al , 2006), most of the methane in atmosphere is originated from biological processes in anoxic environment Rice (*Oryza sativa* L), generally cultivated in submerged anoxic soil environment, has been identified as one of the major sources of anthropogenic methane contributing about 10–15% to global CH_4 emissions (Neue, 1993) Rice fields occupy

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approximately 15% of the world's arable lands (Maclean et al , 2002) India produces about 80 Mt of rice on an area of 42 3 million ha, corresponding to 28% of the global rice land (Sharma et al , 1995) The rice growing areas of India can be broadly categorized into rainfed and irrigated farming types representing about 52% and 48% of the total rice area of the country, respectively (Babu et al , 2006) Worldwide emission of methane from rice has been extrapolated from reports from China, India, Vietnam, Korea, and the Philippines to be from 21 to 30 Tg/year (Sass et al , 2002)

Methane production in rice fields is the result of interactions of soil processes involving plants and microbes (Verburg et al , 2006) Flooding rice fields promotes anaerobic fermentation of carbon sources supplied by the rice plants and other incorporated organic substrates resulted in methane production Subsequent methane emission is the result of its production and oxidation in the soil and the transport of the gas from soil to atmosphere through rice plants (Kruger et al 2001) Therefore, the magnitude of methane emission from rice plant is regulated by complex and dynamic interactions among plant, environment and microorganisms

Major sources of substrate for methanogenes are derived from root exudates, and dead plant parts derived from rice plants and incorporated organic matters Therefore, the rate of production and emission of methane, largely depend on the morpho-physiological parameters like growth characteristics and photosynthetic efficiency of the rice plant, which in turn influence the supply of substrate for methanogenes for methane production (Sass and Cicerone, 2002) and its subsequent release into the environment (Gogoi et al 2005) Photosynthetic carbon products are stored in plants and are incorporated in the soil in the form of exudates and dead plant parts (Jimenez and Lal, 2006), which are utilized by the microorganisms for methanogenesis On the other hand, grain yield of rice is strongly determined by the photosynthetic efficiency It is evident that rice grain production must increase to feed an increasing world-population, while at the same time, methane emissions from paddy fields need to be reduced Thus, the relationship between rice grain yield and the emission of methane from paddy fields emerges as a major scientific and policy issue Therefore, in the present study, attempt was made to establish a relationship of methane emission with photo-synthate partitioning, growth and yield characteristics of rice plant This approach may help to develop an economically feasible, environmentally sound biological mitigation option of methane from paddy fields

2. Materials and methods

2 1 Experimental site and field procedure

The experiment was conducted in a farmer's field at village Amolapam, located near Tezpur Central University campus of North Bank Plain Zone of Assam, situated at northeastern part of India (Fig 1) Methane emission from paddy fields was estimated during the rainfed summer rice (locally known as *Ahu*) growing season (April–July) of 2006 Soil samples were collected from the experimental field before the start of the experiment and analyzed for various parameters, the results of which are presented in Table 1 The field was ploughed, puddled thoroughly to 15 cm depth and levelled Rice seedlings (30-day-old) of two improved cultivars, *viz* Disang and Luit, developed by Regional Rice Research Station, Titabor, of Assam Agricultural University, were transplanted (spacing 20 cm × 20 cm, 2 seedling $hill^{-1}$) in four replicated plots (5 m × 5 m = 25 m^2) Fertilizers were applied at the rate of 40 20 20 kg N_2–P_2O_5–K_2O ha^{-1} in the form of urea, single super phosphate (SSP) and murate of potash (MOP) as recommended in the package of practice of Assam Agricultural University, India

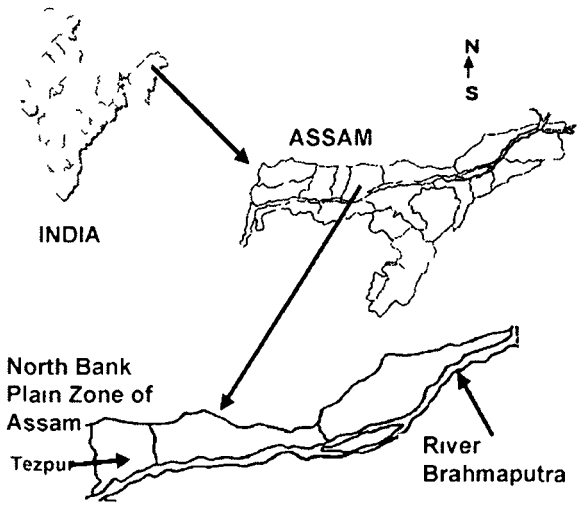

Fig 1 Experimental site at North Bank Plain Agro-climatic Zone of Assam northeast India

Table 1
Soil characteristics of the experimental field

Soil characteristics	Values
pH	5 40 ± 0 06[a]
EC (mmhos/100 g)	0 43 ± 0 02
CEC (meq 100 g^{-1})	10 20 ± 0 55
Bulk density (g cm^{-3})	0 85 ± 0 02
Clay (%)	30 10 ± 0 49
Silt (%)	41 40 ± 0 90
Sand (%)	28 50 ± 0 44
Organic carbon (%)	0 94 ± 0 01
Available nitrogen (kg ha^{-1})	375 40 ± 1 73
Available phosphorus (kg ha^{-1})	36 20 ± 0 83
Available potassium (kg ha^{-1})	237 70 ± 2 03
Total iron (ppm)	445 00 ± 2 08
Total manganese (ppm)	20 00 ± 1 00
Total copper (ppm)	17 00 ± 1 53
Total zinc (ppm)	23 00 ± 1 53

[a] Standard error

2 2 Gas sampling and estimation of methane emission

Methane flux from rice field was recorded at 7-day intervals, from 0 days of transplanting till 15 days after harvest, by using a static chamber technique described by Parashar et al (1996) Briefly, chambers of 50 cm length, 30 cm width and 70 cm height made of 6 mm thick acrylic transparent sheets were used for gas sampling The rectangular U-shaped aluminium channel (50 cm × 30 cm) cm) supported on an aluminium frame (50 cm × 30 cm × 15 cm) was used to accommodate the chamber The aluminium channel was pre-inserted into the soil to a depth of 15 cm well in advance (7 day before transplanting) During gas sampling, the aluminium tray was filled with water to a depth of 2 5 cm, which acted as air seal when the Perspex box was placed on the tray A battery-operated fan inside the Perspex box homogenized the air in the chamber before sampling Gas samples were drawn from the chambers by airtight syringe (50 ml volume) fitted with a three-way stop cock and a fine needle The needle was inserted gently to the Perspex box through a self-sealing rubber septum Immediately after drawing the gas sample by moving the stop cock, the syringe was made airtight Gas sampling was done twice a day (morning 09 00 a m , afternoon 2 00 p m) at intervals of 15 min (0, 15, 30 and 45 min) The temperature inside the Perspex chamber was recorded by a thermometer inserted through a rubber septum installed at the top of the box Barometric pressure and water level inside the chamber were measured during each sampling for calculating air volume at standard temperature and pressure (STP) Gas samples were brought to the laboratory in the Department of Environmental Science, Tezpur Central University, Tezpur, and concentration was determined by gas chromatograph (Varian, Model 3800, USA) fitted with flame ionization detector (FID) and Chromopack capillary column (50 cm long, 0 53 mm out side and 1 μm inside diameter) Column, detector and injector temperature were maintained at 50, 90 and 150 °C, respectively Gas chromatograph was calibrated periodically by methane standard obtained from National Physical Laboratory, New Delhi Methane flux was calculated from the temporal increase in the methane concentration inside the box using the equation of Parashar and Fisher (1998) and the average of morning and evening fluxes were considered as the flux value for the day Cumulative methane emission for the entire growth period was computed by plotting the methane efflux values against the days of sampling, and the area covered under the plot of such relationship was expressed as seasonal integrated flux (E_{sif}) in g m^{-2} Results of methane efflux values were processed and plotted against days after transplanting (DAT)

2 3 Plant and soil parameters

Morphological parameters such as plant height, tiller number, leaf number, leaf area, root length and root volume were recorded at weekly intervals Dry weights of different plant parts (leaf-blade, leaf-sheath, culm and root) were taken at 7-day intervals by drying the plant parts separately in an oven at 75 °C Leaf area and root length was measured by portable laser leaf area meter assembled with a root measurement attachment (CID, Model CI-203, USA) Total organic carbon of the soil was determined by standard wet oxidation method following the protocol given by Jackson (1973) Field water level was recorded during each gas-sampling period Soil temperature was measured with a soil thermometer inserted into the soil (5 0 cm depth) near the Perspex chamber

2 4 Photosynthetic rate

Leaf photosynthesis was measured at weekly interval (from 7 day after transplanting till harvest) by an infra-red gas analyzer (LI-6400 portable photosynthesis system, LI-COR, USA), under ambient environmental conditions Measurement was done following the method of Baig et al (1998) The photosynthetic rate (μmol CO_2 m^{-2} s^{-1}) of intake leaf was measured between 11 00 and 11 30 a m The middle portion of a fully expanded, healthy-green 2nd leaf from the top was used for measurement up to the pre-flowering stage, and the flag leaf was used for photosynthesis measurement from the panicle initiation stage of the crop Leaves were held in the chamber until values of photosynthesis were observed to be as constant as possible (steady state), which was rapid (3 ± 4 min) due to the similarity of environmental conditions of inside and outside the leaf chamber Leaves were kept at steady state for 1 min before measurements were taken

2 5 Statistical analysis

Measurements of different parameters for all the growth stages were replicated four times The significance or non-significance of a given variance was determined by calculating the respective 't' and S E ± values (Gomez and Gomez, 1984), considering the cultivars as source of variation Correlation of methane flux with other parameters (means of all different growth stages) was done by Pearson correlation method

3. Results

Measurement of methane fluxes from two different rice cultivars grown in rainfed condition indicated cultivar differences in methane emission (Fig 2) Higher seasonal integrated methane flux was recorded in cultivar Disang (E_{sif} = 1 38 g m^{-2}), compared to Luit (E_{sif} = 0 96 g m^{-2}) Despite the cultivar differences in methane fluxes, a similar seasonal pattern of CH_4 emission from both the rice cultivars was observed In both the cases, methane flux was initially very low, and then increased with the advancing age of the

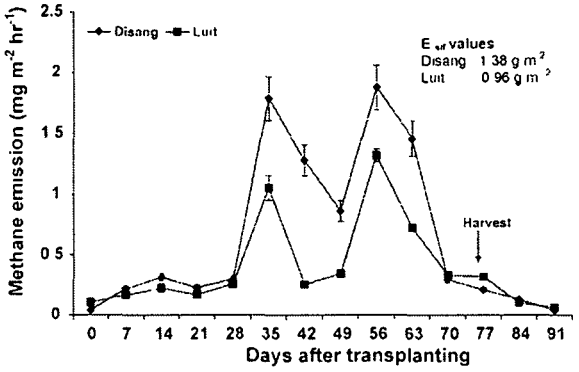

Fig 2 Methane emission (mg m^{-2} h^{-1}) from rice cultivars grown under rainfed condition Data presented are means ± SEd (vertical bars, SEd values are multiplied by 10) E_{sif} = seasonal integrated flux

rice plants. In both the cultivars, two distinct methane emission peaks were detected; one at active vegetative growth stage (35 days after transplanting), and the other at panicle initiation stage (56 days after transplanting). The emission peaks of methane were observed in both the cultivars at the same age of plants due to similarity in their growth duration. Methane flux was found to decline at the ripening stage of the cultivars during the later part of crop growth. The rate of methane emission declined after panicle initiation stage in both the varieties and reduced to a negligible level at harvest. Similar results are reported by other workers (Singh et al., 1999). The organic carbon content, like methane flux, was initially low, reaching maximum at active tillering and panicle initiation stage (Fig. 3). A highly significant positive correlation was observed between methane emission and soil organic carbon content for both the cultivars (Table 2).

Meteorological parameters (rainfall, minimum and maximum temperature) during the entire crop growing period were recorded (Fig. 4). Water regime plays an important role in the process of methanogenesis in rice soil (Kongchum et al., 2006). Seasonal rainfall kept the experimental field submerged during most of the growth period, except at 49 days after transplanting and at harvest

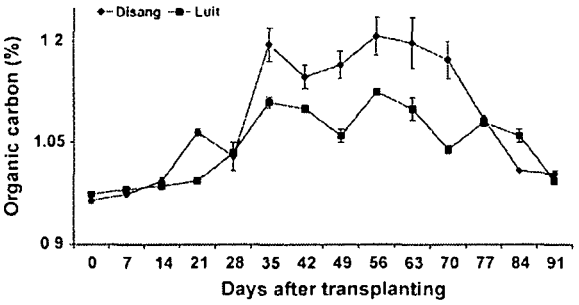

Fig 3 Organic carbon (%) of the experimental field planted with rice cultivars grown under rainfed condition Data presented are means ± SEd (vertical bars, SEd values are multiplied by 10)

Table 2
Correlation between plant and soil parameters and seasonal methane emission from rice cultivars grown under rainfed condition

Parameters	Correlation with methane emission	
	Disang	Luit
Plant height	0.4407*	0 4414*
Leaf number	0 6564*	0 5532*
Tiller number	0 5389*	0 4266*
Leaf area	0 7058**	0 5122*
Root volume	0 4280*	NS
Root length	0 6071*	0 4709*
Root dry weight	0 5614*	0 4977*
Organic carbon	0 7815**	0.7548**
Leaf-blade dry weight	0.4532*	0 4481*
Leaf-sheath dry weight	0 4182*	0.4450*
Culm dry weight	NS	NS

NS non-significant
* Correlation is significant at the 0 05 level of significance
** Correlation is significant at the 0 01 level of significance

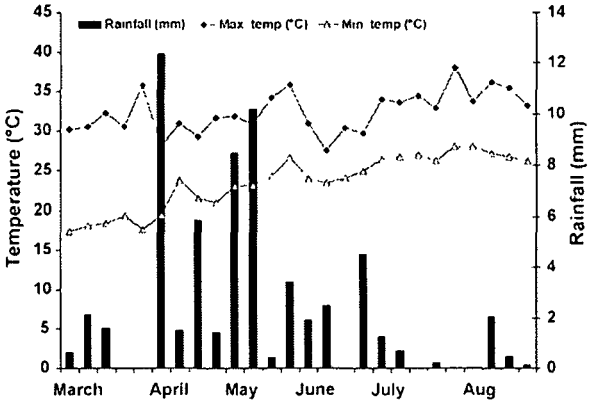

Fig 4. Meteorological parameters during the crop growing season

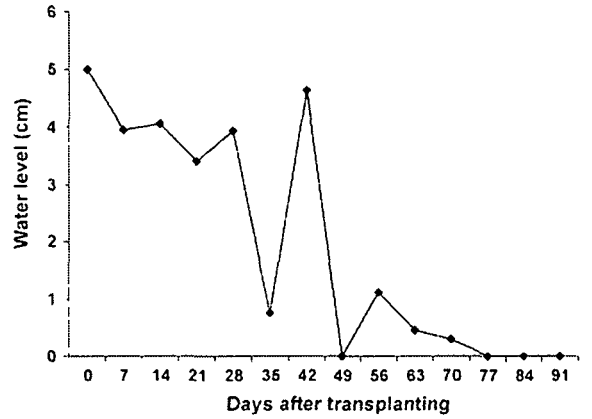

Fig 5 Water level (cm) of the experimental field planted with rice cultivars grown under rainfed condition.

Table 3
Comparison of growth parameters (plant height, leaf number, tiller number and dry weight of leaf-blade, leaf-sheath and culm per hill) between two rice cultivars grown under rainfed condition

Parameters	Cultivars	Days after transplanting									
		7	14	21	28	35	42	49	56	63	70	77
Plant height (cm)	Disang	25 63**	28 30NS	42 56NS	48 58**	53 26**	61 17**	67 27**	71 79**	71 94**	72 25**	72 47**
	Luit	23 46**	28 64NS	42 10NS	52 21**	57 22**	66 21**	77 15**	81 95**	82 13**	82 43**	82 62**
	t values	4 322	0 055	0 256	7 787	10 042	7 688	16 393	17 208	18 015	18 049	18 416
Leaf number (hill^{-1})	Disang	14 50NS	25 92**	34 75**	59 03**	61 28**	62 95**	67 13**	68 30**	63 68**	59 88**	45 58**
	Luit	14 83NS	20 92**	28 83**	51 35**	54 10**	55 60**	57 43**	57 65**	53 05**	49 05**	35 05**
	t values	0 177	3 900	3 875	27 757	16 579	19 471	12 797	22 836	23 479	28 448	20 390
Tiller number (hill^{-1})	Disang	2 25NS	6 42NS	12 67*	14 33**	14 83**	15 23**	14 68**	14 25**	13 25**	12 43**	11 33**
	Luit	2 50NS	4 83NS	11 75*	13 30**	13 50**	13 58**	13 58**	13 33**	12 28**	11 53**	10 30**
	t values	1 964	2 165	3 667	5 704	8 020	16 855	10 914	10 262	14 085	9 194	7 137
Leaf blade dry weight (g hill^{-1})	Disang	0 095NS	0 675NS	0 933**	2 596**	3 953**	5 959**	8 932**	9 958**	9 468**	9 331**	8 639**
	Luit	0 096NS	0 68NS	0 819**	2 096**	3 071**	4 944**	7 879**	8 922**	9 073**	8 870**	7 550**
	t values	0 570	0 504	25 828	22 683	37 344	34 397	23 067	40 694	8 083	10 341	14 984
Leaf sheath dry weight (g hill^{-1})	Disang	0 094**	0 106NS	0 441NS	2 661**	3 561**	6 077**	9 032**	9 700**	9 511**	9 353**	9 249**
	Luit	0 096**	0 115NS	0 407NS	2 073**	3 061**	5 037**	8 391**	9 260**	9 367**	8 849**	8 226**
	t values	0 812	2 262	3 969	12 791	18 969	34 927	19 665	17 409	7 307	17 153	28 505
Culm dry weight (g hill^{-1})	Disang	0 083NS	0 134NS	0 260**	0 656NS	0 921**	1 385**	3 268**	3 472**	3 505**	3 546NS	3 579NS
	Luit	0 086NS	0 137NS	0 206**	0 671NS	0 772**	1 083**	2 635**	3 096**	3 385**	3 507NS	3 533NS
	t values	0 696	1 145	11 085	0 807	4 605	11 950	10 896	5 330	5 993	1 888	2 282

NS non-significant
* Significant at 5% level of significance
** Significant at 1% level of significance

(Fig 5), which intensifies soil reduction and favours methanogenesis (Bharati et al , 2001) In this study, recorded soil temperatures were found to be within the range of 26–37 °C, which is reported to be suitable for methanogenic bacteria for methane production (Nouchi et al , 1990)

Data recorded on plant height, leaf number, leaf area and number of tillers for rice varieties are presented in Table 3 and Fig 6 Higher plant vigour, in the form of leaf number, leaf area and tiller number, were recorded in cultivar Disang over the cultivar Luit Leaf number in both the cultivars increased gradually up to the panicle initiation stage and declined thereafter Methane emission was found to be positively correlated with leaf number and leaf area in both the cultivars (Table 2) After the maximum tillering stage, some tillers did not survive, and consequently, total number of tillers was found to decline Results of the present investigation are in confirmation with the earlier report on rice by this group (Gogoi et al , 2003, 2005)

Photosynthetic rates of the two cultivars were recorded at weekly interval (Fig 7) During the entire vegetative growth phase (up to 49 days after transplanting), higher photosynthetic rate was recorded in Disang, compared to the

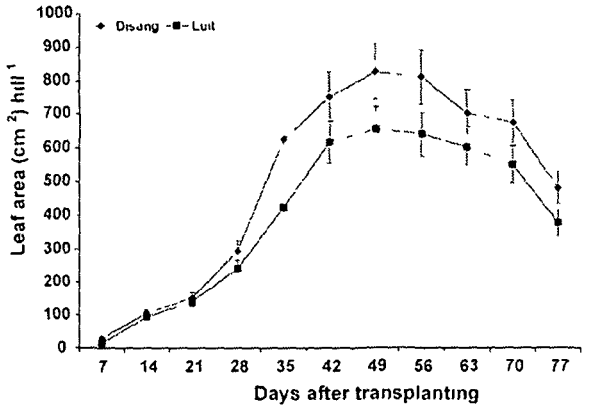

Fig 6 Leaf area (cm^2) per hill of rice cultivars grown under rainfed condition Data presented are means ± SEd (vertical bars, SEd values are multiplied by 10)

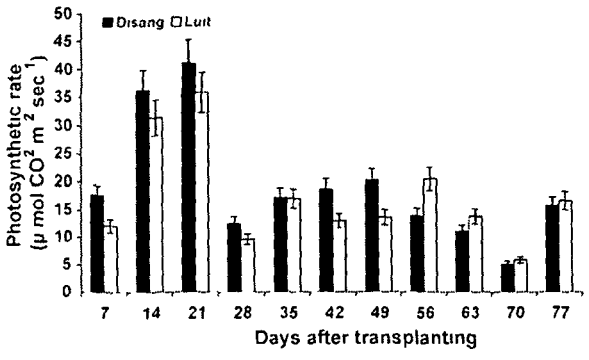

Fig 7 Photosynthetic rate (μmol CO_2 m^{-2} s^{-1}) of rice cultivars grown under rainfed condition Data presented are means ± SEd (vertical bars, SEd values are multiplied by 10)

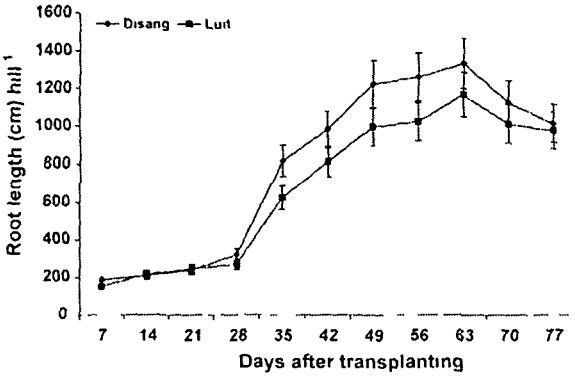

Fig 8 Root length (cm) per hill of rice cultivars grown under rainfed condition Data presented are means ± SEd (vertical bars SEd values are multiplied by 10)

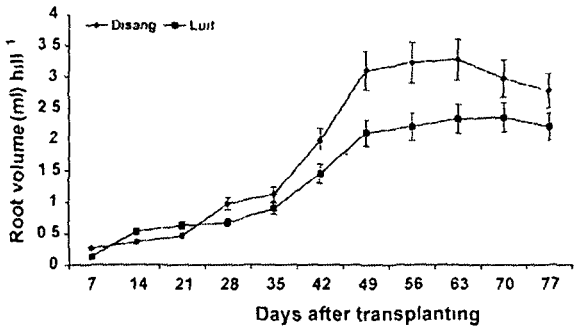

Fig 9 Root volume (ml) per hill of rice cultivars grown under rainfed condition Data presented are means ± SEd (vertical bars SEd values are multiplied by 10)

cultivar Luit However, from the panicle initiation stage (i e from 56 days after transplanting), the trend was found to be reversed higher photosynthetic rate was recorded in cultivar Luit than that of cultivar Disang In cultivar Disang, higher root growth in terms of length, volume and dry weight from the active vegetative growth till maturity of the crop was recorded (Figs 8–10) Dry weight of above ground plant parts (leaf-blade and leaf-sheath) also significantly differed in the two cultivars (Table 3)

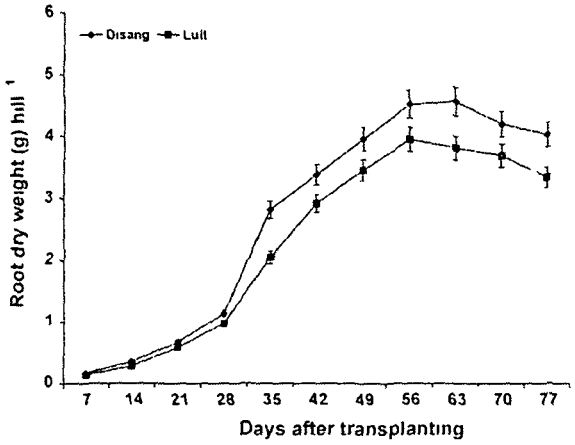

Fig 10 Root dry weight (g) per hill of rice cultivars grown under rainfed condition Data presented are means ± SEd (vertical bars SEd values are multiplied by 10)

4. Discussion

The low emission of methane after transplanting might be due to the limited carbon sources, low levels of methanogenesis and poor conduction of methane from the soil to the atmosphere through rice plants with under-developed biomass (Satpathy et al , 1997) Some workers reported an initial methane emission maximum that occurs shortly after transplanting, apparently caused by the fermentation of easily degradable soil organic matter in the soil (Sass and Fisher, 1992) However, if the amount of easily degradable carbon is low at the beginning of the season, no initial peak of methane emission develops (Neue et al , 1995) In the present study, no distinct peaks were detected soon after transplanting, which may be due to low amount of soil organic carbon (Table 1) as suggested by Neue et al (1995) Very little increase in methane flux was recorded from 7 to 21 days after transplanting in both the cultivars Methane formation during the early and mid-season growth stages of rice, which last for 40–50 days in tropical climates, results primarily from microbial decomposition of freshly incorporated crop residues (Wassmann et al , 2000) Therefore, the first methane emission peak, observed at active vegetative growth stage of the crop, may be associated with decomposition of organic matter derived from left over plant residues in the form of paddy straw and dead roots from the previous crop, which served as substrate for methanogenes (Xu et al , 2000) The second highest CH_4 flux maxima, during the panicle initiation stage, were attributed to the higher availability of substrates in the rice rhizosphere (Adhya et al , 1994, Mitra et al , 2005) Root exudates provide important carbon sources for CH_4 production by supplying energy for microbial activity in rice growing soil Dissolved organic carbon (a mobile form of soil organic carbon) in the rice root zone increased with plant growth, whereas in the non-root zone, it remained low throughout the growing season (Lu et al , 2000), indicating that the primary source of this carbon fraction was plant-derived Increased organic matter input through root exudates and decaying roots might be responsible for the observed increases in CH_4 flux at panicle initiation stage, a mechanism suggested by Bouwman (1991) and Wassmann et al (1993) Drop in methane emission at the end of the crop growth period, observed in the present investigation (Fig 2), may be due to decline in conductance possibly because of reduced permeability of the root epidermal layer (Nouchi et al , 1994), limited carbon availability and a decline in porosity and transport capacities of the roots (Wang and Patrick, 1995)

It is evident that regulation of seasonal variation of CH_4 flux was under the control of organic carbon available in the soils Lu et al (2000) also established a similar trend and reported that the seasonal change in methane emission was closely related to the change in organic carbon concentration in the root zone Towards the end of the crop growth, when methane emission was negligible, soil organic carbon also recorded lower values in both the cultivars (Fig 3) Carbon loss from soils could not be compensated by the carbon input through plant photosynthesis (Zhijian et al , 2006) because the increase in soil organic carbon was less than the net plant carbon input (Lu et al , 2002) This may be the reason of low soil organic carbon recorded at the end of the crop growing season in the present investigation Similar decline in dissolved organic carbon content was recorded by other workers and such decrease at the end of the season was also attributed to decline in root exudation and decomposition of dissolved organic carbon pool (Lu et al , 2000)

Positive correlation between methane emission and tiller number was recorded in this study (Table 2) Aulakh et al (2002) observed similar results and suggested that increase in methane transport capacity with increased number of tillers was due to enhanced density and amount of aerenchyma The lower methane emission rate during early part of the plant growth is partly due to the lower methane transport capacity of the rice plant at this stage due to less leaf number (Table 3), leaf area (Fig 6), tiller number (Table 3), and root growth (Figs 8–10)

Methane emission and photosynthetic characteristic of rice are reported to be closely related (Denier van der Gon et al , 2002, Sass and Cicerone, 2002) Through photosynthesis, carbon is stored in different plant parts and through decomposition and root exudation, is incorporated into soil (Jimenez and Lal, 2006) On an average, 30–60% of the net photosynthetic carbon is allocated to the root, and as much as 40–90% of this fraction enters the soil in the form of rhizo-deposition (Lynch and Whipps, 1990, Marschner, 1996) Lu et al (2002) confirmed, by pulse labeling of C, that about 1–5% of the net assimilation was incorporated into soil Interestingly, within 3–5 h after assimilation, part of photosynthesized C was transported to the rhizosphere, transformed to CH_4, and emitted to the atmosphere (Minoda and Kimura, 1994) Rhizo-deposition was shown to be the main origin of CH_4 evolved from rice fields (Kimura et al , 2004) From the observed photosynthetic rate, dry matter allocation to different plant parts and methane emission rate, we hypothesize that higher photosynthetic rate during the vegetative growth phase of Disang resulted in profuse vegetative growth of the plant including the root (Table 3, Figs 6 and 8–10) The percentage distribution of photosynthetically derived assimilates to soil was exponentially correlated to the rate of root growth (Lu et al , 2002) Greater root growth provides greater surface area for diffusion of CH_4 into roots and greater air space (Singh et al , 1999), which might be the reason for enhancement of CH_4 emission from the cultivar Disang Amount of root exudates was reported to be positively correlated to root dry matter production (Wang and Adachi, 2000), and therefore, higher root weight and density increase the methane production and transport (Ladha et al , 1986) Methane production potential of soil planted with rice plant was higher than that of the unplanted soil (Zhongjun et al , 2006), which indicates a direct role of rice root on methane production In the present investigation, significant positive correlation was observed between methane emission and root growth, in terms of length and dry weight in both the cultivars (Table 2) Disang recorded higher dry weight of leaf-blade and leaf-sheath compared to Luit, which may be due to higher photosynthetic assimilation in different parts of that cultivar Larger aboveground biomass signifies the conduit effect of rice plants (Mariko et al , 1991) Methane emission and shoot dry weight, in terms of leaf-blade and leaf-sheath dry weight, were found to be positively correlated (Table 2) Increase in root or aboveground biomass during plant growth until flowering determines the corresponding increase in methane transport capacity (Aulakh et al , 2002) The contributions of plant biomass, both in CH_4 production in rhizosphere and its subsequent transport to atmosphere, explain the relation among the higher rate of photosynthesis, greater biomass accumulation and higher CH_4 emission from cultivar Disang during the vegetative growth stage Huang et al (2002) found that the carbon released as methane is approximately equivalent to 3% and 4 5% of photosynthetically fixed carbon in the biomass for low and high emission cultivars, respectively Recently, Weiguo et al (2006) reported that elevated CO_2 significantly increased methane emission (as high as 58%) compared with ambient CO_2 These findings clearly indicate the relationship of photosynthesis and methane emission As expected, comparatively lower photosynthetic rate recorded in Luit during this period lead to reduced vegetative growth, which resulted in low methane emission from this cultivar

After panicle initiation, photosynthetic rate was higher in cultivar Luit compared to Disang Despite higher photosynthetic rate, Luit recorded lower methane emission during this period This trend may be associated with the pattern of photosynthates translocation towards the developing panicle Earlier studies revealed that there is an inverse relationship between rice plants' capacity to store photosynthetically fixed carbon and seasonally emitted methane (Sass and Cicerone, 2002), and on an average, $11 \pm 4\%$ of the carbon, not allocated to rice grains, was emitted as methane (Denier van der Gon et al , 2002) In the present study, higher values of thousand grain weight, number of panicle per m^2, filled grain percentage and higher yield were recorded (Table 4) in cultivar Luit, indicating higher photosynthate partitioning towards the panicles and developing grains As expected, dry weight of developing panicle was significantly higher in cultivar Luit (Fig 11) during the whole grain filling period Higher rate of photosynthesis during the reproductive stage, along with efficient translocation of assimilates, as evident by superior yield attributing

Table 4
Comparisons of yield and yield attributing parameters of two rice cultivars grown under rainfed condition

Cultivars/parameters	Cultivar		t values
	Disang	Luit	
1000 grain weight (g)	19 00a*	20 25b*	3 286
Spikelet sterility (%)	14 00a*	12 87b*	2 742
Panicle plant^{-1}	9 33a**	11 03b**	14 20
Spikelet panicle^{-1}	72 94a	73 31a	0 898
Panicle (m^{-2})	234 00a*	236 00b*	2 449
Panicle length (cm)	20 20a**	21 98b**	4 219
Panicle dry weight (g plant^{-1})	11 56a**	12 61b**	3 962
Yield (t ha^{-1})	2 78a**	2 99b**	12 86

In each row, means with similar letters are not significantly different
* Significant at 5% level of significance
** Significant at 1% level of significance

parameters, resulted in better grain yield in cultivar Luit On the other hand, lower vegetative growth of this cultivar in terms of smaller leaf area, reduced leaf number, lower root length and volume, and lower dry weight in different plant part may be attributed to lower methane emission From the recorded data, it is evident that translocation of higher amount of photosynthates towards the vegetative parts during the reproductive phase resulted into larger root and shoot growth in cultivar Disang Leaf number and area, tiller number, root volume and length, and dry weight of different plant parts were significantly higher in this cultivar, whereas yield and all yield attributing parameters like thousand grain weight, number of grain per panicle, number of panicle per m^2, filled grain percentage were inferior compared to cultivar Luit It clearly indicates that in Disang, during the reproductive stage, photosynthesized carbon could not be allocated efficiently to the developing grain Cereal grain yield can be limited either by the supply of assimilate to fill the grain (source limitation) or by the capacity of the reproductive organs to accept the assimilate (sink limitation) (Denier van der Gon et al , 2002) In cultivar Disang, lower photosynthetic rate during the reproductive stage indicated source limitation, whereas low yield development, in spite of higher availability of pre-anthesis, reserves reflected sink

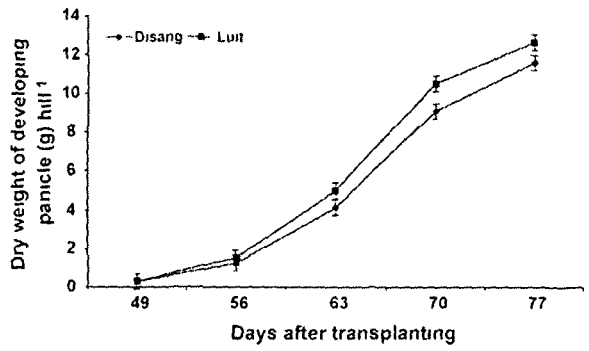

Fig 11 Dry weight (g) per hill of developing panicle grown under rainfed condition Data presented are means ± SEd (vertical bars, SEd values are multiplied by 10)

limitation Lower efficiency of stored photosynthate translocation from different plant parts, inferior capacity of current assimilates supply to the developing grain, along with lower photosynthetic rate, resulted in lower yield in the cultivar Disang In this cultivar, major portion of photosynthates is translocated towards the vegetative parts, as evident from the recorded values on dry weight of root, leaf-blade, leaf-sheath and culm The amount of carbon, not allocated to the developing grain, reflects the yield gap and a portion of the photosynthetically assimilated carbon associated with the yield gap entered the soil as rhizodeposition This resulted in higher substrate availability of methanogenes and this might be a major reason for more emission of methane from this cultivar

5. Conclusion

The findings of the present investigation indicate that the use of high-yielding cultivars with low photosynthate-carbon translocation towards root would result in lower CH_4 emission Therefore, screening of existing rice cultivars, and initiation of breeding programme for new cultivars with low photosynthate partitioning to root could offer an important methane mitigation option Rice cultivars having higher photosynthate carbon allocation capacity to rice grain and lower translocation of carbon to root for methanogenes might help to reduce methane emission from paddy fields, without compromising the grain yield Therefore, development of new plant type of rice with balance source and sink capacity may be important in mitigating methane emission from paddy field

References

Adhya, T K , Rath, A K , Gupta P K , Rao, V R Das, S N Parida, K M , Parashar, D C , Sethunathan N , 1994 Methane emission from flooded rice fields under irrigated conditions Biol Fertil Soils 18, 245–248
Aulakh, M S , Wassmann, R , Rennenberg, H , 2002 Methane transport capacity of twenty two rice cultivars from five major Asian rice growing countries Agric Ecosyst Environ 91, 59–71
Babu, Y J , Li, C Frolking, S , Nayak, D R , Adhya, T K 2006 Field validation of DNDC model for methane and nitrous oxide emissions from rice-based production systems of India Nutr Cycl Agroecosys 74, 157–174
Baig, M J , Swain, P, Murty, K S , 1998 The photosynthetic efficiency of some elite rice hybrids and restorers Photosynthetica 35, 241–246
Batjes, N H , Bridges, E M , 1992 A review of soil factors and processes that control fluxes of heat, moisture, and greenhouse gases Technical Paper 23 International Soil Reference and Information Centre, Wageningen
Bharati K , Mohanty, S R Rao V R , Adhya, T K , 2001 Influence of flooded and non-flooded conditions on methane efflux from two soils planted to rice Chemosphere Global Change Sci 3 25–32
Bouwman, A F , 1991 Agronomic aspects of wetland rice cultivation and associated methane emissions Biogeochemistry 15, 65–88
Denier van der Gon, H A C , Kropff, M J , van Breemen, N , Wassmann, R , Lantin, R S , Aduna, E , Corton, T M , van Laar, H H , 2002 Optimizing grain yields reduces CH_4 emission from rice paddy fields Proc Natl Acad Sci U S A 99, 12021–12024

Gogoi N, Baruah, K K, Gogoi, B, Gupta, P K, 2005 Methane emission characteristics and its relations with plant and soil parameters under irrigated rice ecosystem of northeast India Chemosphere 59, 1677–1684

Gogoi, N, Baruah, K K, Gupta, P K, Das, K K, 2003 Physiological parameters of rice (*Oryza sativa* L) associated with emission of methane from different agroecosystem Indian J Plant Physiol (Special Issue) 597–601

Gomez, K A, Gomez, A A, 1984 Statistical Procedures for Agricultural Research, second ed John Wiley and Sons, New York, 680 pp

Huang, Y, Sass, R L, Fisher, F M, 2002 Methane emission from Texas rice paddy soils 2 Seasonal contribution of rice biomass production to CH_4 emission Global Change Biol 3, 491–500

Jackson, M L, 1973 Soil Chemical Analysis Prentice Hall of India Pvt Ltd, New Delhi

Jimenez J, Lal, R, 2006 Mechanism of sequestration in soils of Latin America Crit Rev Plant Sci 25, 337–365

Keppler, F, Hamilton, J T G, Brab, M, Rockmann, T, 2006 Methane emissions from terrestrial plants under aerobic conditions Nature 439, 187–191

Kimura, M, Murase, J, Lu, Y, 2004 Carbon cycling in rice field ecosystems in the context of input, decomposition and translocation of organic materials and fates of their end products (CO_2 and CH_4) Soil Biol Biochem 36, 1399–1416

Kongchum, M, Bollich, P K, Hudnall, W H, DeLaune, R D, Lindau, C W, 2006 Decreasing methane emission of rice by better crop management Agron Sust Dev 26, 45–54

Kruger, M, Frenzel, P, Conrad, R, 2001 Microbial processes influencing methane emission from rice fields Global Change Biol 7, 49–63

Ladha, J K, Tirol, A C, Darby, L G, Caldo, G, Ventura, W, Watanabe, L, 1986 Plant associated N_2 fixation (C_2H_2 reduction) by five rice varieties and relationship with plants growth characters as affected by straw application Soil Sci Plant Nutr 32, 1962–1972

Lelieveld, J, Crutzen, P J, Dentener, F J, 1998 Changing concentration, lifetimes and climate forcing of atmospheric methane Tellus B 50, 128–150

Lu, Y, Wassmann, R, Neue, H-U, Huang, C, 2000 Dynamics of dissolved organic carbon and methane emissions in a flooded rice soil Soil Sci Soc Am J 64, 2011–2017

Lu, Y, Watanabe, A, Kimura, M, 2002 Input and distribution of photosynthesized carbon in a flooded rice soil Biogeochem Cycle 16, 1085

Lynch, J M, Whipps, J M, 1990 Substrate flow in the rhizosphere Plant Soil 129, 1–10

Maclean, J L, Dawe, D C, Hardy, B, Hettel, G P, 2002 Rice Almanac International Rice Research Institute, Los Banos, Philippines

Mariko, S, Harazono, Y N, Nouchi, I, 1991 Methane in flooded soil, water and the emission through rice plants to the atmosphere Environ Exp Botany 31, 343–350

Marschner, H, 1996 Mineral Nutrition of Higher Plants Academic Press, London

Minoda, T, Kimura, M, 1994 Contribution of photosynthesized carbon to the methane emitted from paddy fields Geophys Res Lett 21, 2007–2010

Mitra, S, Aulakh, M S, Wassmann, R, Olk, D C, 2005 Triggering of methane production in rice soils by root exudates effects of soil properties and crop management Soil Sci Soc Am J 69, 563–570

Neue, H U, 1993 Methane emission from rice fields Biosciences 43, 466–474

Neue, H U, Wassmann, R, Lantin, R S, 1995 Mitigation options for methane emission from rice-fields In Peng, S, Ingarm, K T, Neue, H U, Ziska, L H (Eds), Climate Change and Rice Springer-Verlag, Berlin, Heidelberg, pp 136–144

Nouchi, I, Mariko, S, Aoki, K, 1990 Mechanism of methane transport from the rhizosphere to the atmosphere through rice plants Plant Physiol 94, 59–66

Nouchi, I, Hosono, T, Aoki, K, Minami, K, 1994 Seasonal variation in CH_4 flux from rice paddies associated with CH_4 concentration in soil water, rice biomass and temperature and its modelling Plant Soil 161, 195–208

Parashar, D C, Fisher Jr, F M, 1998 Methane from irrigated rice cultivation In Sharma, C, Mitra, A P (Eds), Global Environment Chemistry Narosa Publishing House, New Delhi, pp 77–93

Parashar, D C, Mitra, A P, Gupta, P K, 1996 Methane budget from paddy fields in India Chemosphere 33, 737–757

Sass, R L, Mosier, A, Zheng, X H, 2002 Introduction and summary international workshop on greenhouse gas emissions from rice fields in Asia Nutr Cycl Agroecosyst 64 ix–xv

Sass, R L, Fisher, F M, 1992 CH_4 emission from paddy fields in the United State gulf coast area In Minami, K, Mosier, A, Sass, R (Eds), CH_4 and N_2O Global Emissions and Controls from Rice-fields and other Agricultural and Industrial Sources (NIAES Ser 2), pp 65–78

Sass, R L, Cicerone, R J, 2002 Photosynthate allocation in rice plants food production or atmospheric methane Proc Natl Acad Sci U S A 99, 11993–11995

Satpathy, S N, Rath, A K, Ramakrishnan, B, Rao, V R, Adhya, T K, Sethunathan, N, 1997 Diurnal variation in methane efflux at different growth stages of tropical rice Plant Soil 195, 267–271

Sharma, A R, Moorthy, B T S, Rao, K S, Venkateswarlu, B, 1995 Improvement of rice production technology in the conventional areas of eastern India In Deb, D L (Ed), Sustaining Crop and Animal Productivity—The Challenge of the Decade Associated Publishing Co, New Delhi, pp 157–178

Singh, S, Singh, J S, Kashyap, A K, 1999 Methane flux from irrigated rice fields in relation to crop growth and N-fertilization Soil Biol Biochem 31, 1219–1228

Verburg, P H, Bodegom, P M, Denier van der Gon, H A C, Bergsma, A, van Breemen, N O, 2006 Upscaling regional emissions of greenhouse gases from rice cultivation methods and sources of uncertainty Plant Ecol 182, 89–106

Wang, B, Adachi, K, 2000 Differences among rice cultivars in root exudation, methane oxidation, and populations of methanogenic and methanotrophic bacteria in relation to methane emission Nutr Cycl Agroecosyst 58, 349–356

Wang, Z P, Patrick Jr, W H, 1995 Fertilization effects on methane production from anaerobic soil amended with rice straw and nitrogen fertilizers Fertil Res 33, 115–121

Wassmann, R, Buendia, L V, Lantin, R S, Bueno, C S, Lubigan, L A, Umali, A, Nocon, N N, Javellana, A M, Neue, H U, 2000 Mechanisms of crop management impact on methane emissions from rice fields in Los Banos, Philippines Nutr Cycl Agroecosyst 58, 107–119

Wassmann, R, Papen, H, Rennenberg, H, 1993 Methane emission from rice paddies and possible mitigation options Chemosphere 26, 201–217

Weiguo, C, Kazuyuki, Y, Hidemitsu, S, Kazuhiko, K, 2006 Effects of elevated atmospheric CO_2 concentration on CH_4 and N_2O emission from rice soil an experiment in controlled-environment chambers Biogeochemistry 77, 351–373

Xu, H, Cai, Z C, Jia, Z J, Tsuruta, H, 2000 Effect of land management in winter crop season on CH_4 emission during the following flooded and rice growing period Nutr Cycl Agroecosyst 58, 12–18

Zhijian, M U, Kimura, S D, Ryusuke, H, 2006 Estimation of global warming potential from upland cropping system in central Hokkaido, Japan Soil Sci Plant Nutr 52, 371–377

Zhongjun, J, Zucong, C, Haruo, T, 2006 Effect of rice cultivar on CH_4 production potential of rice soil and CH_4 emission in a pot experiment Soil Sci Plant Nutr 52, 341–348

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ORIGINAL PAPER

Association between contrasting methane emissions of two rice (*Oryza sativa* L.) cultivars from the irrigated agroecosystem of northeast India and their growth and photosynthetic characteristics

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Abstract Over two consecutive years in the North Bank Plain Zone of Assam, India, during the spring growing season (February–June) of- 2006 and 2007 we examined effects of morpho-physiological characteristics of rice (*Oryza sativa* L.) plants in relation to methane (CH_4) emission from paddy fields. Traditional cultivar "Agni" and modern improved cultivar "Ranjit" were grown in light textured loamy soil under irrigation. A higher seasonal integrated methane flux (E_{sif}) was recorded from "Agni" compared to "Ranjit". Both cultivars exhibited an emission peak during active vegetative growth and a second peak at panicle initiation. Leaf and tiller number, leaf area, length, and volume of root were greater in "Agni", but grain yield and yield-related parameters such as increased photosynthate partitioning to panicles at the expense of roots were greater in "Ranjit". "Ranjit" also photosynthesed faster than "Agni" during panicle development but slower than "Agni" at tillering. In both the years, a higher soil organic carbon content was recorded in plots of "Agni". Our results suggest that in "Agni" enhanced diversion of photosynthate to roots resulted in more substrate being available to methanogenic bacteria in the rhizosphere. Additionally, the more extensive vegetative growth of this cultivar may enhance methane transport from the soil to the above-ground atmosphere.

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Keywords Growth · Methane · Organic carbon · Photosynthesis · Rice

Introduction

The global atmospheric concentration of methane (CH_4) has increased from a pre-industrial value of about 715–1,732 ppb by the early 1990s and to 1774 ppb by 2005 (IPCC 2007). Methane is an important greenhouse gas, and the atmospheric increases account for about 15% of current global warming (Batjes and Bridges 1992). Most methane in the atmosphere originates from anaerobic biology. Although, annual increases in atmospheric CH_4 have slowed recently, possibly because of decreasing anthropogenic emissions from fossil fuel, this is thought to be only a temporary pause (Bousquet et al. 2006).

Most rice (*Oryza sativa* L.) is cultivated in submerged anoxic soils. These have been identified as a major source of anthropogenic methane contributing about 10–15% to global CH_4 emissions (Neue 1993). Rice growing in India can be broadly categorized into rainfed and irrigated farming representing about 52 and 48% of the total rice area, respectively (Babu et al. 2006). Methane production in rice fields such as these is the result of interactions of soil processes involving plants and microbes (Verburg et al. 2006). Flooding the soil promotes anaerobic degradation of photosynthetic carbon supplied by rice plants resulting in methane production whenever redox potentials become sufficiently negative. The major sources of substrate for methanogenic bacteria are root exudates and decaying plant remains (Jimenez and Lal 2006). Therefore, the rate of production and emission of methane is thought to depend on morpho-physiological parameters such as growth and

Table 1 Soil characteristics of the experimental field

Soil characteristics	2006	2007
pH	5.45 ± 0.01	5.36 ± 0.01[a]
EC (mmhos 100 g^{-1})	0.47 ± 0.01	0.45 ± 0.02
CEC (m eq. 100 g^{-1})	10.87 ± 0.15	10.13 ± 0.15
Bulk density (g cc^{-1})	0.87 ± 0.01	0.85 ± 0.01
Clay (%)	31.57 ± 0.12	32.43 ± 0.18
Silt (%)	39.50 ± 0.21	40.27 ± 0.09
Sand (%)	28.93 ± 0.09	27.3 ± 0.15
Organic carbon (%)	0.95 ± 0.01	0.96 ± 0.01
Available nitrogen (kg ha^{-1})	378.67 ± 1.62	371.5 ± 1.27
Available phosphorus (kg ha^{-1})	39.43 ± 0.64	36.83 ± 0.70
Available potassium (kg ha^{-1})	240.90 ± 0.81	236.3 ± 0.701
Total iron (ppm)	431.00 ± 2.65	438.67 ± 0.67
Total manganese (ppm)	19.67 ± 0.88	23 ± 2.08
Total copper (ppm)	17.67 ± 1.45	20.33 ± 1.20
Total zinc (ppm)	24.00 ± 1.53	22.33 ± 1.45

[a] Standard error

photosynthetic efficiency of the rice plant (Sass and Cicerone 2002). On the other hand, grain yield of rice is also strongly affected by photosynthetic efficiency. An important goal is to maximise grain production while reducing methane emissions. The relationship between rice grain yield and the emission of methane from paddy fields is thus a major scientific and policy issue. Several reports document methane emission from the paddy fields of northeast India (Gogoi et al. 2003, 2005) but details of the relationship between growth, photosynthetic efficiency, grain yield and methane emission has yet to be worked out for this region. The present paper addresses this shortcoming.

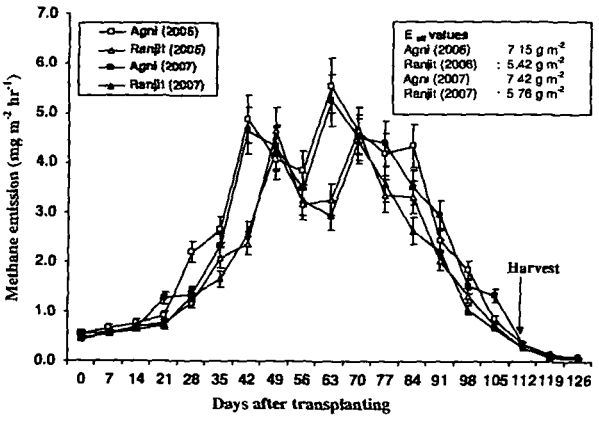

Fig. 1 Methane emission (mg m^{-2} h^{-1}) from rice cultivars grown under irrigation. Data presented are means ± SEd (*vertical bars*; SEd values are multiplied by 10). E_{sir} seasonal integrated flux

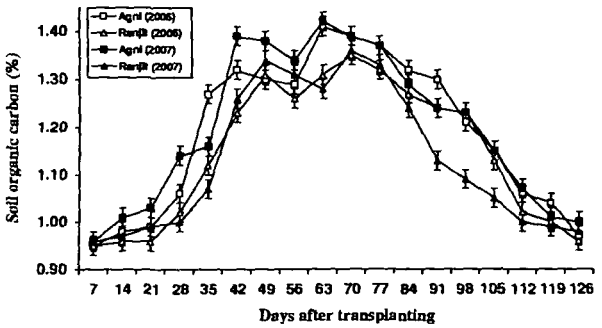

Fig. 2 Organic carbon (%) of the experimental field planted with rice cultivars grown under irrigation. Data presented are means ± SEd (*vertical bars*; SEd values are multiplied by 10)

Materials and methods

Experimental site and field procedure

The experiment was conducted in a farmer's field at Amolapam near Tezpur Central University campus (26°41′N, 92°50′E) in the North Bank Plain Zone of Assam, northeast India. The region is subtropical humid having moderately hot-wet summers and dry winters with a maximum temperature of 39°C (July–August) and minimum of 8°C (December–January). In both years of the present study (2006 and 2007) and during the early period of crop growth (February), temperatures were cool and gradually increased towards maturation (May–June). Methane emission from paddy fields was estimated during the irrigated spring rice (*Boro* rice) growing season (February–June). Soil samples were collected from the experimental field before the start of each experiment and analysed (Table 1). The field was ploughed, puddled thoroughly to 15-cm depth and levelled. Rice seedlings (35-day-old; 5–6 leaf stage) of two cultivars, viz. "Agni" (traditional) and "Ranjit" (improved and developed by Regional Rice Research Station, Titabor, Assam Agricultural University) were transplanted (spacing: 20 cm × 20 cm; 2 seedling per hill) in four replicated plots (5 × 5m = 25 m^2). Fertilizer was applied at the rate of 60:30:30 kg N–P–K ha^{-1} in the form of urea, single super phosphate (SSP) and murate of potash (MOP) as recommended in the package of normal practice of Assam Agricultural University. Fields were submerged from transplanting to panicle initiation (70 days after transplanting, DAT).

Gas sampling and estimation of methane emission

Methane flux from rice field was recorded at 7-day intervals until 15 days after harvest using the static chamber technique described by Parashar et al. (1996). Briefly, chambers 50 cm long, 30 cm wide and 70 cm tall made of

Table 2 Comparison of morphological parameters (plant height, leaf number, leaf area and tiller number per hill) between two rice cultivars grown under irrigated condition

	Days after transplanting															
	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112
Plant height (cm)																
2006																
Agni	18.13**	26.25**	39.13**	62.75**	66.00**	76.38**	92.38**	102.63**	126.88**	135.25**	137.63**	137.81**	138.02**	138.19**	138.38**	139.08**
Ranjit	13.00**	20.25**	29.13**	43.50**	58.88**	67.75**	70.00**	84.88**	109.00**	116.50**	116.67**	116.87**	117.02**	117.11**	117.25**	117.32**
t values	5.22	5.20	8.20	13.34	6.25	4.35	14.76	10.37	7.69	7.745	8.763	8.876	8.99	8.96	8.96	9.70
2007																
Agni	18.73**	19.98**	24.73**	30.33**	40.30**	46.44**	79.26**	99.98**	108.63**	123.85**	127.34**	129.20**	129.98**	131.00**	131.95**	133.10**
Ranjit	16.03**	17.93**	21.80**	26.88**	35.21**	42.18**	58.70**	78.79**	97.99**	112.53**	113.99**	115.69**	115.83**	116.40**	116.64**	117.31**
t values	3.96	6.81	6.53	9.72	3.57	4.86	66.05	75.13	19.10	27.72	38.05	15.19	20.84	43.80	49.77	72.919
Leaf no. (hill^{-1})																
2006																
Agni	10.25^{NS}	14.75*	21.75**	44.50**	51.50**	64.00*	90.5*	105.50*	123.50*	130.75**	126.25**	123.75*	120.25**	117.75*	113.75*	109.75**
Ranjit	9.00^{NS}	11.00*	16.25**	24.75**	32.00**	57.50*	83.00*	99.25*	113.50*	124.00**	120.25**	117.75*	114.50**	112.00*	110.00*	100.75**
t values	0.75	3.15	3.74	10.20	6.50	2.73	3.21	2.84	2.97	4.246	5.308	2.51	4.09	2.70	2.60	4.665
2007																
Agni	8.80**	11.48**	13.75**	16.93**	24.85**	32.10**	74.65**	82.98**	106.95**	125.00**	112.33**	91.45**	87.63**	85.93**	84.03**	82.05**
Ranjit	6.63**	9.85**	11.65**	14.00**	18.33**	27.28**	58.18**	73.45**	97.68**	112.40**	99.95**	80.28**	76.68**	75.10**	73.40**	71.80**
t values	4.43	6.01	6.12	8.19	8.76	10.12	11.09	32.83	7.95	31.07	13.33	14.27	16.48	17.80	21.96	18.54
Leaf area (hill^{-1})																
2006																
Agni	37.62^{NS}	59.59**	123.45**	141.16**	199.48**	300.77**	509.80**	792.86**	1022.95**	1688.80**	1590.35**	1513.21**	1361.41*	1267.94**	987.80**	783.04**
Ranjit	34.00^{NS}	46.62**	85.87**	94.71**	157.20**	252.45**	418.50**	629.86**	884.92**	1589.95**	1498.40**	1354.84**	1293.44*	1184.15**	879.48**	606.35**
t values	2.31	6.43	10.77	12.76	6.98	6.45	12.34	15.10	4.94	7.57	6.53	3.85	2.58	2.95	23.66	42.996
2007																
Agni	*38.61***	*45.16***	*58.84***	*102.26***	*197.56***	*255.01***	*490.24***	*750.94***	*927.24***	*1518.76***	*1422.08***	*1313.30***	*1216.86***	*1148.70***	1032.21**	807.29**
Ranjit	32.61**	37.09**	46.12**	83.67**	166.86**	213.17**	395.24**	607.51**	823.54**	1411.37**	1300.17**	1195.98**	1046.98**	974.15**	902.97**	707.98**
t values	4.19	3.56	6.42	5.09	8.65	4.76	19.27	18.15	10.33	9.54	7.50	8.35	6.83	4.43	5.35	9.96
Tiller no. (hill^{-1})																
2006																
Agni	0.00^{NS}	0.00^{NS}	4.50**	9.00**	11.50**	17.75**	25.00**	24.75**	24.00**	23.50**	22.25**	21.25**	20.50**	19.75**	18.75**	16.75**
Ranjit	0.00^{NS}	0.00^{NS}	2.50**	6.50**	8.25**	15.5**	20.50**	20.25**	20.25**	20.25**	19.00**	16.75**	16.00**	15.75**	14.25**	12.50**
t values	–	–	4.24	4.33	5.04	5.10	5.10	4.93	4.33	4.07	4.47	5.76	6.04	6.41	4.93	4.58

Table 2 continued

	Days after transplanting														
	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112
2007																
Agni	0.00	1.80*	3.33^{NS}	7.85**	9.18**	11.28**	15.83**	16.55**	17.10**	16.68**	15.48**	15.15**	14.45**	14.25**	14.13**	14.03**
Ranjit	0.00	1.48*	3.58^{NS}	6.23**	7.98**	9.30**	12.30**	13.45**	15.10**	15.05**	13.40**	13.10**	12.55**	12.25**	12.10**	12.00**
t values	–	3.30	1.01	4.31	7.43	12.42	9.25	5.07	5.39	3.45	4.76	5.50	8.23	8.32	8.89	8.53

NS Non-significant

* Significant at 5% level of significance

** Significant at 1% level of significance

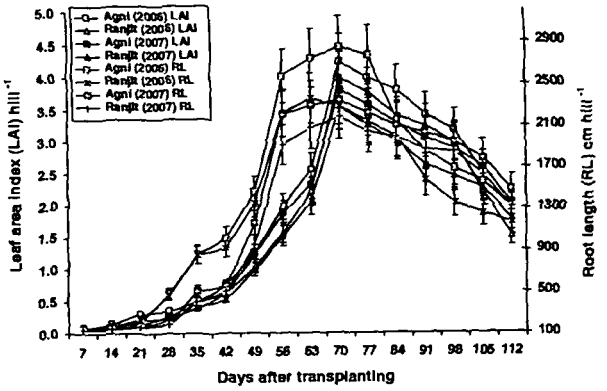

Fig. 3 Leaf area index and root length (cm hill^{-1}) and of rice cultivars grown under irrigated condition. Data presented are means ± SEd (*vertical bars*; SEd values are multiplied by 10)

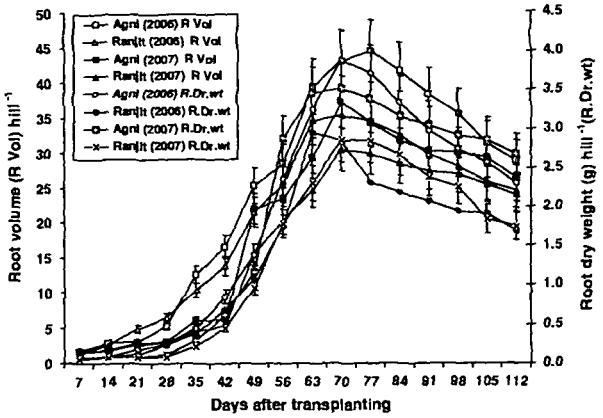

Fig. 4 Root volume (ml hill^{-1}) and root dry weight (g hill^{-1}) of rice cultivars grown under irrigated condition. Data presented are means ± SEd (*vertical bars*; SEd values are multiplied by 10)

6-mm-thick clear acrylic sheet were used for gas sampling. Rectangular U shaped aluminium channelling (50 cm × 30 cm) resting on an aluminium frame (50 cm × 30 cm × 15 cm) was used to support the chambers. The aluminium channels were inserted into the soil to a depth of 15 cm 7 days before transplanting. During gas sampling, the aluminium trays were filled with water to a depth of 2.5 cm. This acted as an air seal for the flux boxes. A battery-operated fan inside each box thoroughly mixed the air in the chamber before sampling. Gas samples were drawn from the chambers using a 50 ml airtight syringe fitted with a three-way stop-cock and a fine needle that was inserted through a self-sealing rubber septum. Gas was sampled four times at intervals of 15 min at 0900 hours and again at 1400 hours. Barometric pressure, temperature and water level inside the chamber were measured during

Table 3 Comparison of growth parameters (leaf blade dry weight, leaf sheath dry weight, culm dry weight and shoot dry weight per hill) between two rice cultivars grown under irrigated condition

	Days after transplanting															
	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112
Leaf blade dry weight (g hill^{-1})																
2006																
Agni	0.19^{NS}	0.25*	0.49**	0.70**	1.19**	1.95*	2.16*	6.02**	8.17**	10.08*	8.94*	8.40*	7.86**	6.74*	5.62**	5.45**
Ranjit	0.17^{NS}	0.21*	0.26**	0.57**	1.06**	1.69*	2.07*	5.65**	7.83**	9.85*	8.64*	8.14*	7.36**	6.54*	5.17**	5.04**
t values	1.57	2.48	10.65	4.99	4.45	3.35	2.74	4.69	5.35	2.96	3.03	2.78	4.58	2.71	5.02	4.77
2007																
Agni	0.19**	0.21^{NS}	0.30**	0.41**	0.99**	1.73**	2.40**	5.26**	7.42**	9.11**	8.68**	7.88**	7.30**	5.40*	4.96**	4.84**
Ranjit	0.16**	0.19^{NS}	0.23**	0.34**	0.83**	1.28**	1.90**	4.25**	4.94**	7.20**	7.15**	6.94**	5.76**	4.87*	4.33**	4.25**
t values	3.84	2.21	5.47	5.16	8.56	8.54	21.21	18.10	33.70	30.64	15.52	11.22	11.08	2.77	5.36	9.93
Leaf sheath dry weight (g hill^{-1})																
2006																
Agni	0.06*	0.08**	0.10**	0.17**	0.29**	0.40**	0.48**	1.29**	2.41**	3.96**	3.97**	4.08**	3.98**	3.72**	3.28**	3.15**
Ranjit	0.04*	0.05**	0.07**	0.11**	0.15**	0.19**	0.40**	1.02**	2.01**	3.08**	3.08**	3.09**	3.05**	2.98**	2.39**	2.24**
t values	2.69	3.78	6.45	6.57	8.78	16.60	5.06	8.72	8.65	20.44	23.37	34.50	22.80	5.18	9.43	11.01
2007																
Agni	0.08**	0.09*	0.11NS	0.11*	0.24*	0.40**	0.51**	1.58**	2.90**	4.01**	4.08**	4.41**	4.40**	4.21**	4.12**	4.07**
Ranjit	0.06**	0.07*	0.10NS	0.12*	0.23*	0.31**	0.44**	0.89**	1.48**	2.81**	3.15**	3.40**	3.37**	3.31**	3.29**	3.23**
t values	3.97	2.84	2.12	2.45	2.84	7.23	14.85	46.07	53.93	47.06	20.14	21.88	11.27	6.39	8.44	17.37
Culm dry weight (g hill^{-1})																
2006																
Agni	0.15^{NS}	0.26**	0.39**	0.53**	1.27*	1.72**	2.30**	5.77**	7.97**	8.41**	8.76**	9.37**	9.90**	10.12**	11.42**	11.21**
Ranjit	0.09^{NS}	0.18**	0.28**	0.40**	0.90*	1.10**	1.75**	4.65**	6.06**	6.97**	7.54**	7.95**	8.13**	8.43**	9.14**	9.07**
t values	1.63	2.83	7.14	5.00	2.71	4.31	3.26	6.49	23.43	6.00	5.10	6.99	22.02	16.64	9.45	10.33
2007																
Agni	0.13^{NS}	0.18**	0.24**	0.29**	0.73**	1.25**	3.09**	6.00**	6.52**	8.05**	8.92**	9.04**	9.75**	10.48**	10.56**	10.65**
Ranjit	0.11^{NS}	0.16**	0.21**	0.24**	0.53**	0.63**	1.17**	4.73**	5.59**	6.75**	6.84**	8.10**	8.11**	8.96**	9.33**	9.97**
t values	2.41	7.79	9.53	9.64	7.26	36.83	156.77	72.65	29.83	45.64	90.80	15.55	32.16	58.15	49.12	40.86
Shoot dry weight (g hill^{-1})																
2006																
Agni	0.40^{NS}	0.59**	0.99**	1.39**	2.76**	4.07**	4.93*	13.07**	18.55**	22.44**	21.67**	21.84**	21.74**	20.58**	20.32**	19.80**
Ranjit	0.31^{NS}	0.45**	0.60**	1.07**	2.11**	2.98**	4.22*	11.32**	15.90**	19.90**	19.26**	19.18**	18.55**	17.95**	16.70**	16.34**
t values	1.87	3.72	9.20	6.15	3.94	5.20	3.48	6.43	17.76	7.53	6.67	9.18	16.24	11.56	11.66	14.62

Table 3 continued

	Days after transplanting														
	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112
2007																
Agni	0.40**	0.48**	0.64**	0.81**	1.95**	3.39**	6.00**	12.83**	16.83**	21.17**	21.67**	21.34**	21.45**	20.09**	19.63**	19.56**
Ranjit	0.33**	0.42**	0.54**	0.70**	1.59**	2.22**	3.50**	9.87**	12.01**	16.76**	17.14**	18.44**	17.24**	17.15**	16.96**	17.44**
t values	7.82	3.79	5.72	5.47	10.94	17.56	83.95	37.53	49.09	46.23	28.88	15.52	16.95	9.28	13.13	19.41

NS Non-significant

* Significant at 5% level of significance

** Significant at 1% level of significance

Table 4 Correlation between plant and soil parameters and seasonal methane emission from rice cultivars grown under irrigated condition

Parameters	Correlation with methane emission			
	2006		2007	
	Agni	Ranjit	Agni	Ranjit
Plant height	0.38^{NS}	0.39*	0.34^{NS}	0.31^{NS}
Leaf no.	0.51*	0.53*	0.58*	0.59*
Leaf area	0.45^{NS}	0.51*	0.46^{NS}	0.49*
LAI	0.45^{NS}	0.51*	0.46NS	0.49*
Tiller no.	0.70**	0.77**	0.67**	0.64**
Root length	0.70**	0.75**	0.55*	0.53*
Root volume	0.55*	0.61*	0.48^{NS}	0.45^{NS}
Root dry weight	0.50*	0.55*	0.46^{NS}	0.50*
Leaf blade dry weight	0.50*	0.53*	0.56*	0.51*
Leaf sheath	0.22^{NS}	0.30^{NS}	0.21^{NS}	0.12^{NS}
Culm dry weight	0.13^{NS}	0.16^{NS}	0.17^{NS}	0.07^{NS}
Shoot dry weight	0.29^{NS}	0.34^{NS}	0.32^{NS}	0.23^{NS}
Organic carbon	0.90**	0.88**	0.95**	0.96**

NS Non-significant

* Correlation is significant at the 0.05 level of significance

** Correlation is significant at the 0.01 level of significance

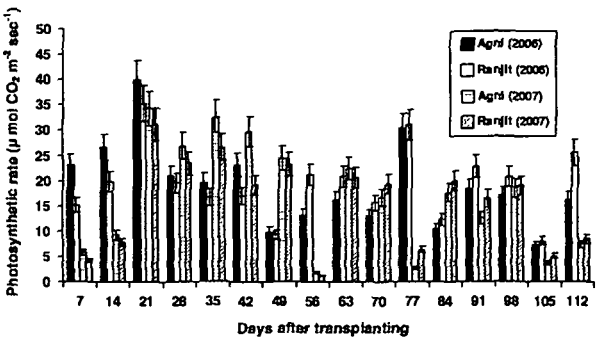

Fig. 5 Photosynthetic rate (μmol CO_2 m^{-2} s^{-1}) of rice cultivars grown under irrigation. Data presented are means ± SEd (*vertical bars*; SEd values are multiplied by 10)

each sampling. This permitted calculation of air volumes at standard temperature and pressure (STP). Methane in gas samples was determined using a gas chromatograph (Varian, Model 3800) fitted with flame ionization detector (FID) and Chromopack capillary column (50 cm long, 0.1 μm inside diameter). Column, injector and detector temperature were maintained at 50, 90 and 150°C, respectively. Gas chromatograph was calibrated with a methane standard obtained from National Physical Laboratory, New Delhi. Methane flux was calculated from the temporal increase in the CH_4 concentration inside the box using the equation of Parashar and Fisher Jr (1998) and the

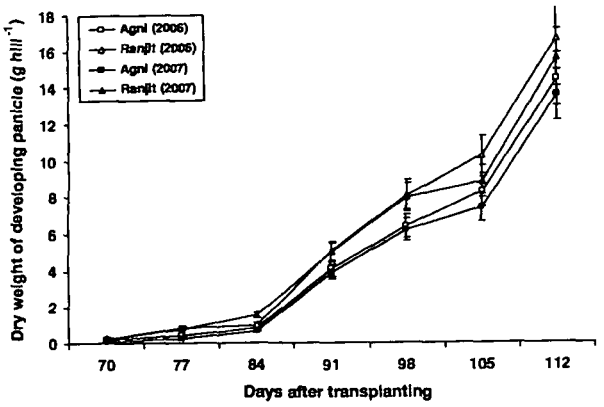

Fig. 6 Dry weight (g hill^{-1}) of developing panicle of rice cultivars grown under irrigation. Data presented are means ± SEd (*vertical bars*; SEd values are multiplied by 10)

average of morning and evening fluxes were considered as the flux value for the day. Cumulative CH_4 emission for the entire growth period was computed by plotting the CH_4 efflux values against the days of sampling and the area covered under the plot of such a relationship was expressed as the seasonal integrated flux (E_{sif}) in g m^{-2}.

Plant and soil parameters

Plant height, tiller number, leaf number, leaf area, leaf area index, root length and root volume were recorded weekly. Dry weights of leaf-blade, leaf-sheath, culm, root and shoot were taken at 7-day-intervals after drying at 75°C. Leaf area and root length was measured with a portable laser leaf area meter (CID, Model CI-203) with root measurement attachment. Soil samples were collected at 7-day-intervals from 15 cm depth from the four replicate plots. Total organic carbon of the soil was determined by standard wet oxidation method (Jackson 1973). Field water level was recorded every 7 days and soil temperature was measured with a soil thermometer inserted into the soil (5.0 cm depth) near the Perspex chamber.

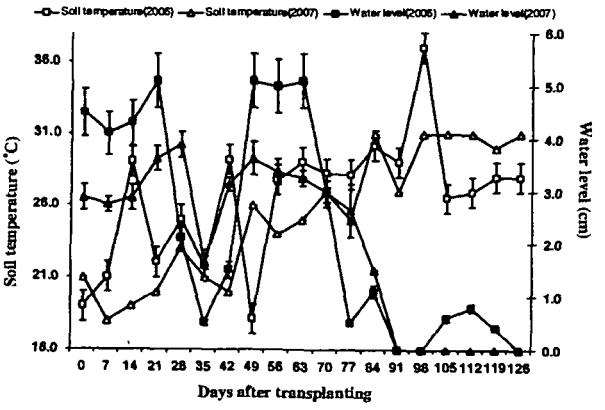

Fig. 7 Soil temperature (°C) and water level (cm) of the experimental field planted with rice cultivars grown under irrigation. Data presented are means ± SEd (*vertical bars*; SEd values are multiplied by 10)

Photosynthetic rate

Leaf photosynthesis (μmol CO_2 m^{-2} s^{-1}) was measured at weekly intervals between 11.00 and 11.30 a.m. from 7 days after transplanting until harvest using an infra-red gas analyzer (LICOR, LI-6400 portable photosynthesis system) under ambient environmental conditions as described by Baig et al. (1998). The middle portion of the youngest fully expanded leaf (second from the top) was used up to the pre-flowering and the flag leaf used thereafter.

Statistical analysis

Significance of differences between means were assessed using Student's "*t*" and standard errors considering cultivars as the source of variation. Correlations of methane flux with other parameters (means of all different growth stages) were made by the Pearson correlation method.

Results

Two-years of measurement from "Agni" and "Ranjit" grown in irrigated condition indicated cultivar differences in methane emission (Fig. 1). Higher seasonal integrated methane flux (E_{sif}) was recorded for cultivar "Agni" (E_{sif} in 2006 = 7.15 g m^{-2}; E_{sif} in 2007 = 7.42 g m^{-2}) compared to "Ranjit" (E_{sif} in 2006 = 5.42 g m^{-2}; E_{sif} in 2007 = 5.76 g m^{-2}). Despite these differences, a similar seasonal pattern of CH_4 emission from both cultivars was observed in both years with methane flux being initially very low and then increasing with advancing age of the rice plants. Two distinct methane emission peaks were detected. The first was during active vegetative growth (42 DAT in "Agni"; 49 DAT in "Ranjit"). The second at panicle initiation (63 DAT in "Agni"; 70 DAT in 'Ranjit'). The emission peaks of methane were observed at the same age of plants in both the years due to the similarity in growth duration of the cultivars. Methane emission declined after panicle initiation stage in both the cultivars and was negligible at grain harvest.

Soil organic carbon content, like methane flux, was initially low, reached a maximum at active tillering and panicle initiation (Fig. 2). In both the years, highly significant positive correlations were found between methane emission and soil organic carbon content for both the

Table 5 Comparisons of yield and yield attributing parameters of two rice cultivars grown under irrigated condition

Cultivars/parameters	2006			2007		
	Agni	Ranjit	*t* value	Agni	Ranjit	*t* value
1,000 grain weight (g)	19 13*	20 50*	2 52	18 30**	19 98**	6 69
Filled grain (%)	74 50**	78 50**	3 80	74 75^{NS}	77 50^{NS}	2 23
Panicle plant^{-1}	9 75^{NS}	10 50	1 70	9 75*	10 75*	2 45
Spikelet panicle^{-1}	87 25^{NS}	89 25^{NS}	2 19	86 75	88 75	2 19
Panicle (m^{-2})	243 75^{NS}	262.50^{NS}	1 70	252 25^{NS}	261 50^{NS}	1 21
Panicle length (cm)	20 25*	22 00*	3 17	20 25*	21 50*	2 84
Panicle dry weight (g plant^{-1})	14 37**	16 60**	5 96	13 52**	15 57**	5 58
Yield (t ha^{-1})	3 03**	3 77**	4 06	2 99**	3 59**	5 45

NS Non-significant

* Significant at 5% level of significance

** Significant at 1% level of significance

cultivars (Table 4) Water regime plays an important role in the process of methanogenesis (Kongchum et al 2006) Seasonal rainfall and applied irrigation kept the experimental field submerged during most of the growth period (Fig 7) This intensified bacterial chemical reduction in the soil thus favouring methanogenesis (Bharati et al 2001) Soil temperatures ranged between 18 and 37°C in 2006, and 18 and 31°C in 2007 and were thus warm enough to support vigorous methanogenic bacterial activity (Nouchi et al 1990)

Plant height, leaf number, leaf area and tiller number were higher in "Agni" compared to "Ranjit" Leaf number, leaf area and leaf area index in both the cultivars increased gradually up to the panicle initiation stage and declined thereafter (Table 2, Fig 3) Methane emission was positively correlated with these growth parameters in both cultivars (Table 4) in both years After the maximum tillering stage, some tillers died and consequently total number of tillers declined In both the years, the two cultivars showed highly significant positive correlations between tiller number and methane emission Results of the present investigation confirm our earlier preliminary report (Gogoi et al 2005)

During vegetative growth (up to 49 DAT in 2006, and up to 63 DAT in 2007) faster photosynthetic rates were recorded for "Agni", compared to "Ranjit" (Fig 5) However, at subsequent panicle initiation, panicle development and ripening stages (i e from 56 DAT in 2006, and from 70 DAT in 2007) the position reversed with photosynthetic rate being faster for cultivar "Ranjit" In "Agni", higher root growth in terms of length, volume and dry weight from the active vegetative growth until maturity of the crop was seen in both the years (Figs 3, 4) Dry weight of above ground plant parts (leaf-blade, leaf-sheath, culm and shoot) also significantly differed between the two cultivars (Table 3)

Discussion

The low methane flux recorded soon after transplanting was probably the outcome of limited respirable soil carbohydrate resulting in minimal methanogenesis The small size of the plants at this time also provided a poor conduit for methane to escape by diffusion from the soil to the atmosphere (Satpathy et al 1997) Very little increase in methane flux was recorded until the third week after transplanting Subsequent methane release during the early and mid-season growth stages of rice plants is thought to result primarily from microbial decomposition of freshly incorporated crop residues (Wassmann et al 2000) Therefore, the first methane emission peak, observed at active vegetative growth stage of the crop (42 DAT in Agni, 49 DAT in Ranjit), is probably the result of decomposition of organic matter derived from left over plant residues such as paddy straw and dead roots from the previous crop (Xu et al 2000) The second CH_4 flux maxima, occurring during panicle initiation (63 DAT in Agni, 70 DAT in Ranjit) is attributed to greater availability of substrates in the rice rhizosphere (Adhya et al 1994, Mitra et al 2005) as already suggested by Bouwman (1991) and Wassmann et al (1993) During this period, root exudates and cell debris are expected to provide carbon sources for CH_4 production by supplying energy and carbon substrate for microbial activity In support of this view, organic carbon in the rice root zone is known to increase with plant growth, whereas in the non-root zone it remains low throughout the growing season (Lu et al 2000) The drop in methane emission at the end of crop growth (Fig 1) may be explained by a decline in gas conductance possibly because of reduced permeability of root epidermis (Nouchi et al 1994), limited carbon discharge into the rhizosphere and a decline in porosity and longitudinal transport capacity of the roots (Wang and Patrick Jr 1995)

Regulation of seasonal variation of CH_4 flux was therefore seemingly under prime control by the availability of organic carbon in the soil. Lu et al. (2000) also established a similar trend and reported that the seasonal change in methane emission was closely related to the change in organic carbon content in the root zone. Towards the end of the crop growth, when methane emission was negligible, soil organic carbon also recorded low for both cultivars (Fig. 2). This trend was observed in both years. Decline in organic carbon content at the end of the season was attributed to decline in root exudation and rate of decomposition of soil organic carbon (Lu et al. 2000). Our observation of increase in methane transport capacity with increased number of tillers (Table 4) may be the result of enhanced aerenchyma formation and associated increase in aerial discharge area (Aulakh et al. 2002). Conversely, slower methane emission when plants were small may, in part, be the result if less well-developed aerenchyma and smaller leaf areas for gas discharge (Table 2), smaller root system for methane uptake (Figs. 4, 5, 6) and a smaller rate of carbon release into the soil.

Methane emission and photosynthetic characteristic of the rice plant have been reported by others to be closely related (Denier van der Gon et al. 2002; Sass and Cicerone 2002). A major portion of the net photosynthetic carbon is allocated to the root and a significant amount of this fraction enters the soil (Lu et al. 2002) in the form of rhizodeposition (Lynch and Whipps 1990; Marschner 1996), a part of which, in flooded rice soils, will be transformed to CH_4, and emitted to the atmosphere (Minoda and Kimura 1994). In our work, higher photosynthetic rates were recorded for cultivar "Agni" compared to "Ranjit" (Fig. 5) at the vegetative stage and this presumably underpinned its more extensive vegetative growth, including greater leaf area (Tables 2, 3; Figs. 3, 4) and more root (Table 4) which in turn would support more vigorous methanogenesis via an enhanced assimilate discharge into the soil (Lu et al. 2002; Weiguo et al. 2006; Wang and Adachi 2000) and gas absorption. The larger root system of cultivar "Agni" is thus one of the reasons for the increased the CH_4 production and transport, a mechanism as already suggested by Ladha et al. (1986). Dry weight of above ground plant parts also significantly differed in the cultivars (Table 3). These findings clearly indicate an indirect relationship of photosynthesis with CH_4 emission. During the grain filling period, photosynthetic rate was higher in cultivar "Ranjit" even though it emitted less CH_4 than "Agni" at this time. This seeming contradiction may be explained in terms of preferential translocation of photosynthate towards the developing panicle rather than the root system (Denier van der Gon et al. 2002).

In the present investigation, yield and yield-related parameters were recorded from the plants grown outside the Perspex box. Yu et al. (2006) observed that temperature inside the box was increased up to 18°C during gas sampling (with a final temperature inside the chamber up to 46°C), which caused significant yield reduction. However we did not observe such abrupt rate of increase in temperature, and such high temperature was not recorded inside the box. On average, only 4–6°C increase in temperature inside the box was recorded (highest final temperature recorded was 37.5°C) during panicle differentiation and anthesis of the crop. Therefore, it is logical to assume that yield parameters recorded from the plants grown outside the box did not influence our interpretation of results.

We conclude that higher grain yield and superior yield-related parameters of cultivar "Ranjit" (Table 5) indicate higher photosynthate partitioning towards the panicles and developing grains (Fig. 6). On the other hand, reduced vegetative growth in terms of smaller leaf area, lesser root length and volume, and reduced dry weight in different plant parts may explain the lower CH_4 emissions from this cultivar. In "Agni", photosynthetic carbon could not be allocated efficiently to the developing grain during the reproductive stage (Fig. 6), with major portion of photosynthates being translocated towards the vegetative parts, including the roots and thus available for rhizo-deposition. This resulted in higher substrate availability of methanogenesis and thus explains the larger emissions of CH_4 from cultivar "Agni". We reported a similar relationship of photosynthate partitioning with CH_4 emission from rainfed rice (Das and Baruah 2008).

References

Adhya TK, Rath AK, Gupta PK, Rao VR, Das SN, Parida KM, Parashar DC, Sethunathan N (1994) Methane emission from flooded rice fields under irrigated conditions. Biol Fertil Soils 18:245–248

Aulakh MS, Wassmann R, Rennenberg H (2002) Methane transport capacity of twenty two rice cultivars from five major Asian rice growing countries. Agric Ecosyst Environ 91:59–71

Babu YJ, Li C, Frolking S, Nayak DR, Adhya TK (2006) Field validation of DNDC model for methane and nitrous oxide emissions from rice-based production systems of India. Nutr Cycl Agroecosyst 74:157–174

Baig MJ, Swain P, Murty KS (1998) The photosynthetic efficiency of some elite rice hybrids and restorers. Photosynthetica 35: 241–246

Batjes NH, Bridges EM (1992) A review of soil factors and processes that control fluxes of heat, moisture, and greenhouse gases. Technical Paper 23. International Soil Reference and Information Centre, Wageningen

Bharati K, Mohanty SR, Rao VR, Adhya TK (2001) Influence of flooded and non-flooded conditions on methane efflux from two soils planted to rice. Chemosphere Glob Chang Sci 3:25–32

Bousquet P, Ciais P, Millwe JB, Dlugokencky FJ, Hauglustaine DA, Prigent C, Van der Werf GR, Peylin P, Brunke EG Carouge C Langenfelds RL, Lathiere J, Papa F, Ramonet M Schmidt M Steele LP Tyler SC White J (2006) Contribution of

anthropogenic and natural sources to atmospheric methane variability Nature 443 439–443

Bouwman AF (1991) Agronomic aspects of wetland rice cultivation and associated methane emissions Biogeochemical 15 65–88

Das K, Baruah KK (2008) A comparison of growth and photosynthetic characteristics of two improved rice cultivars on methane emission from rainfed agroecosystem of north east India. Agri Ecosyst Env (in press)

Denier van der Gon HAC, Kropff MJ, van Breemen N Wassmann R, Lantin RS, Aduna E, Corton TM, van Laar HH (2002) Optimizing grain yields reduces CH_4 emission from rice paddy fields Proc Natl Acad Sci USA 99 12021–12024

Gogoi N, Baruah KK, Gupta PK, Das KK (2003) Physiological parameters of rice (*Oryza sativa* L) associated with emission of methane from different agroecosystem. Indian J Plant Physiol (Special Issue), pp 597–601

Gogoi N, Baruah KK, Gogoi B, Gupta PK (2005) Methane emission characteristics and its relations with plant and soil parameters under irrigated rice ecosystem of northeast India. Chemosphere 59 1677–1684

IPCC (2007) Climate change 2007 the physical science basis summary for policymakers Intergovernmental Panel on Climate Change, Geneva

Jackson ML (1973) Soil chemical analysis Prentice Hall of India Pvt Ltd, New Delhi

Jimenez J, Lal R (2006) Mechanism of sequestration in soils of Latin America. Crit Rev Plant Sci 25 337–365

Kongchum M, Bollich PK, Hudnall W, DeLaune RD, Lindau CW (2006) Decreasing methane emission of rice by better crop management Agron Sustain Dev 26 45–54

Ladha JK, Tirol AC, Darby LG, Caldo G, Ventura W, Watanabe L (1986) Plant associated N_2 fixation (C_2H_2 reduction) by five rice varieties and relationship with plants growth characters as affected by straw application Soil Sci Plant Nutr 32 1962–1972

Lu Y, Wassmann R, Heinz-Ulrich Neue HU Huang C (2000) Dynamics of dissolved organic carbon and methane emissions in a flooded rice soil Soil Sci Soc Am J 64 2011–2017

Lu Y, Watanabe A, Kimura M (2002) Input and distribution of photosynthesized carbon in a flooded rice soil Biogeochem Cycle 16 1085

Lynch JM, Whipps JM (1990) Substrate flow in the rhizosphere Plant Soil 129 1–10

Marschner H (1996) Mineral nutrition of higher plants Academic Press, London

Minoda T, Kimura M (1994) Contribution of photosynthesized carbon to the methane emitted from paddy fields Geophys Res Lett 21 2007–2010

Mitra S, Aulakh MS, Wassmann R, Olk DC (2005) Triggering of methane production in rice soils by root exudates effects of soil properties and crop Management Soil Sci Soc Am J 69 563–570

Neue HU (1993) Methane emission from rice fields Biosciences 43 466–474

Nouchi I, Mariko S, Aoki K (1990) Mechanism of methane transport from the rhizosphere to the atmosphere through rice plants Plant Physiol 94 59–66

Nouchi I, Hosono T, Aoki K, Minami K (1994) Seasonal variation in CH_4 flux from rice paddies associated with CH_4 concentration in soil water, rice biomass and temperature and its modelling Plant Soil 161 195–208

Parashar DC, Fisher Jr FM (1998) Methane from irrigated rice cultivation In Sharma C, Mitra AP (eds) Global environment chemistry Narosa Publishing House, New Delhi, pp 77–93

Parashar DC, Mitra AP, Gupta PK et al (1996) Methane budget from paddy fields in India Chemosphere 33 737–757

Sass RL, Cicerone RJ (2002) Photosynthate allocation in rice plants food production or atmospheric methane Proc Natl Acad Sci USA 99 11993–11995

Satpathy SN, Mishra S, Adhya TK, Ramakrishnan B, Rao VR, Sethunathan N (1997) Cultivar variation in methane efflux from tropical rice Plant Soil 202 223–229

Singh S, Singh JS, Kashyap AK (1999) Methane flux from irrigated rice fields in relation to crop growth and N-fertilization Soil Biol Biochem 31 1219–1228

Verburg PH, Bodegom PM, Denier van der Gon HAC, Bergsma A, van Breemen N (2006) Upscaling regional emissions of greenhouse gases from rice cultivation methods and sources of uncertainty Plant Ecol 182 89–106

Wang B, Adachi K (2000) Differences among rice cultivars in root exudation, methane oxidation, and populations of methanogenic and methanotrophic bacteria in relation to methane emission Nutr Cycling Agroecosyst 58 349–356

Wang ZP, Patrick Jr WH (1995) Fertilization effects on methane production from anaerobic soil amended with rice straw and nitrogen fertilizers Fertil Res 33 115–121

Wassmann R, Buendia LV, Lantin RS et al (2000) Mechanisms of crop management impact on methane emissions from rice fields in Los Banos, Philippines Nutr Cycling Agroecosyst 58 107–119

Wassmann R, Papen H, Rennenberg H (1993) Methane emission from rice paddies and possible mitigation options Chemosphere 26 201–217

Xu H, Cai ZC, Jia ZJ, Tsuruta H (2000) Effect of land management in winter crop season on CH_4 emission during the following flooded and rice growing period. Nutr Cycling Agroecosyst 58 12–18

Yu KW, Chen GX, Xu H (2006) Rice yield reduction by chamber enclosure a possible effect on enhancing methane production Biol Fertil Soils 43 257–261

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Methane emission associated with anatomical and morphophysiological characteristics of rice (*Oryza sativa*) plant

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Plant-mediated transport is the primary route of methane (CH_4) emission from the reduced paddy field to the aboveground atmosphere Experiments were conducted at North Bank Plain Agro-climatic Zone of Assam, India, during monsoon rice-growing season (July to December 2006) to elucidate the influences of anatomical and morphophysiological characteristics of rice (*Oryza sativa* L) cultivars on methane emission from submerged agro-ecosystem Ten rice cultivars were grown in light-textured loamy soil under rainfed uniform field condition Among the 10 cultivars, 5 were traditional rice genotypes commonly grown in the agroclimatic zone and the other 5 were improved high-yielding varieties Wide variation in CH_4 flux was recorded among the rice cultivars, which may be regulated by the difference in anatomical and morphophysiological characteristics of rice plant Microscopic analysis of stem portion showed that high- and medium-CH_4-emitting cultivars recorded higher size of the medullary cavity Leaf area and transpirational rates were also found to be higher in high-CH_4-emitting varieties Scanning electron microscopic analysis revealed higher stomatal frequencies in high-methane-emitting cultivars Data presented in this study suggest that variation in anatomical and morphophysiological characteristics among different rice genotypes may influence CH_4 emission from paddy fields

Introduction

The global atmospheric concentration of methane (CH_4) has increased from a preindustrial value of about 0 715–1 774 parts per million by volume in 2005 (IPCC 2007) Methane gas present in the atmosphere substantially affects the radiative budget of the earth and has predominant impact on the global warming Most of the CH_4 in atmosphere is originated from biological processes in anoxic environment, although there are reports that CH_4 can be emitted from plants under aerobic condition (Keppler and Rockmann 2007, Keppler et al 2006) Submerged paddy fields are one of the dominant anthropogenic sources of methane to the atmosphere, which is estimated as 15% of the global methane emission (IPCC 1994) Flooding of rice fields promotes anaerobic microbial fermentation of organic carbon (Aulakh et al 2000, Hosono and Nouchi 1997, Jimenez and Lal 2006, Schutz et al 1989), resulted in extensive methanogenesis in rice rhizosphere Methane generated by methanogenesis in paddy field is released to the atmosphere by plant-mediated transport, molecular diffusion across the water–air interface and ebullition (Wassmann et al 1996) The transport of methane through the aerenchyma system of the rice plants is known to be the most important of these (Yagi et al 1996) Cheng et al (2006) reported that the CH_4 emitted by plant-mediated transport and

Abbreviations – E_{sif}, seasonal integrated flux, SEM, scanning electron microscopy, STP, standard temperature and pressure

ebullition–diffusion accounted for 86 7 and 13 3% of
[2] total emissions, respectively

Dissolved methane absorbed by the roots can be gasified quickly in the root cortex and transported in the gaseous state to the shoots through the aerenchyma and the lysigenous intercellular space (Nouchi et al 1990) This results in a steep gradient of methane concentration in medullary cavities, where very high concentration of CH_4 can be detected (Wang et al 1997) The air space of the medullary cavity is linked to the lysigenous air space through the aerenchymatous tissues involved in methane transport Although efforts have been made to describe the plant-mediated methane transport, the relation of methane emission with the size of medullary cavity is not well established Recent studies documented a close relationship between methane emission and inherent varietial characteristics of rice plant (Das and Baruah 2008, Gogoi et al 2005) However, information on anatomical and related morphophysiological characteristics such as stomatal frequency and transpirational rate of rice plant associated with emission and transport of methane is scanty Conclusive descriptions of the microstructures regulating plant-mediated methane transport are also not available In the present study, attempts were made to establish a relationship between anatomical and morphophysiological characteristics of rice plant associated with methane emission Information generated by this study can be used in future breeding programme for developing new cultivars having low CH_4 emission potential

Materials and methods

Experimental site and field procedure

[3] The experiment was conducted in a farmer's field, near Tezpur Central University campus (lat 26°41'N, long 92°50'E) of North Bank Plain Agro-climatic Zone of Assam, situated at northeastern part of India Methane emission from paddy fields was estimated during the monsoon rice-growing season (July to December) of 2006 The field was ploughed, puddled thoroughly to 15-cm depth and leveled Rice seedlings (30 day old) of 10 cultivars were transplanted (spacing 20 × 20 cm, 2 seedling $hill^{-1}$) in four replicated plots (5 × 5 m = 25 m^2) Among the cultivars, five were traditional rice cultivars popularly grown in this agroclimatic zone, viz Basmuthi (V_1), Bogajoha (V_2), Choimora (V_3), Rashmisali (V_4) and Lalkalomdani (V_5), and the other five were improved cultivars viz. Mahsuri (V_6), Moniram (V_7), Kushal (V_8), Prafulla (V_9) and Gitesh (V_{10}) developed by Regional Rice Research Station, Titabor, Assam Agricultural University, India The traditional cultivars selected in this experiment exhibit profuse vegetative growth, whereas improved varieties are semidwarf and have superior yield characteristics All the traditional and improved cultivars have almost similar growth phases and crop duration Fertilizers were applied at the rate of 40 20 20 kg N–P–K ha^{-1} in the form of urea, single super phosphate and murate of potash as recommended in the package of practice of Assam Agricultural University, India

Gas sampling and estimation of methane emission

Methane flux from rice field was recorded at 7-day intervals, from 0 days of transplanting till 15 days after harvest, by using a static chamber technique described by Parashar and Fisher (1998) Briefly, Perspex chambers (50 cm length, 30 cm width and 70 cm height for semidwarf cultivars and 50 cm length, 30 cm width and 100 cm height for tall cultivars) made of 6-mm-thick acrylic transparent sheets were used for gas sampling The rectangular *U*-shaped aluminum channel (50 × 30 cm) supported on an aluminum frame (50 × 30 × 15 cm) was used to accommodate the chamber The aluminum channel was preinserted into the soil to a depth of 15 cm 7 day before transplanting During gas sampling, the aluminum channel was filled with water, which acted as air seal when the chamber was placed on the channel A battery-operated fan inside the chamber homogenized the air in the chamber before sampling Gas samples were drawn from the chambers by airtight syringe (50 ml volume) fitted with a three-way stopcock and a fine needle The needle was inserted gently to the chamber through a self-sealing rubber septum Gas sampling was performed twice a day (at 09 00 h and again at 14 00 h) at intervals of 15 min (0, 15, 30 and 45 min) The temperature inside the chamber was recorded by a thermometer inserted through a rubber septum installed at the top of the chamber Barometric pressure and water level inside the chamber were measured during each sampling for calculating air volume at standard temperature and pressure (STP) Methane concentrations of gas samples were estimated by gas chromatograph (Varian model 3800) fitted with flame ionization detector and Chromo- [4]
pack capillary column (50 cm long, 0 53 mm outside and 1 μm inside diameter) Column, injector and detector temperature were maintained at 50, 90 and 150°C, respectively Gas chromatograph was calibrated periodically by CH_4 standard obtained from National Physical Laboratory, New Delhi The chromatogram was recorded in a computer with VARIAN STAR WORKSTATION (version 6 41) software to record peak area and peak height against the retention time The report generated directly gave the concentration of CH_4 in the sample

Table 1. Methane flux (mg m^{-2} h^{-1}), leaf area (cm^2 $hill^{-1}$) and transpiration (mmol H_2O m^{-2} s^{-1}) of 10 rice cultivars grown under wetland conditions In each column, means with the similar letters are not significantly different at $P < 0.05$ level by Duncan's multiple range test

		Days after transplanting																		
		0	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119	126
Methane flux	V_1	1 37a	1 61ab	1 95a	3 14a	3 26a	4 68a	5 36d	7 16a	6 19b	6 25b	7 34a	6 46b	5 59b	5 35a	4 37b	3 14a	0 63b	0 28bc	0 18ab
	V_2	1 35a	1 58a	1 85ab	2 76b	3 12a	4 36b	4 73g	6 27b	6 96a	5 84c	6 08d	7 11a	5 95a	4 98b	4 67a	3 64a	1 71a	0 49a	0 26a
	V_3	1 39a	1 53abc	1 72bc	2 53c	2 90b	3 85c	6 73a	5 65d	5 74c	5 84c	7 06b	5 93d	5 64b	4 94bc	3 96c	2 10bc	1 04b	0 46a	0 21ab
	V_4	1 35a	1 57abc	1 63c	2 26d	3 12a	3 49d	6 27b	5 36e	5 53cd	6 98a	5 66e	5 34e	5 19c	4 64cd	3 91c	2 12bc	0 78b	0 38ab	0 27a
	V_5	1 42a	1 64a	1 93a	2 16de	2 89b	3 18e	5 94c	5 00f	5 35d	5 58d	6 75c	5 30e	5 07c	4 46de	3 97c	1 77bc	0 81b	0 31bc	0 20ab
	V_6	1 38a	1 36e	1 81ab	1 98ef	2 50c	3 03f	4 98f	6 33b	4 90e	5 19e	6 56c	4 94f	4 55f	4 14e	3 60d	1 50bcd	0 83b	0 24bc	0 18ab
	V_7	1 39a	1 54abc	1 73bc	2 13de	2 25d	2 74g	4 59g	5 00f	6 20b	4 81f	5 37f	6 44b	4 73d	4 43de	3 17e	2 22b	0 64b	0 23c	0 18ab
	V_8	1 34a	1 41de	1 82ab	2 11def	2 25d	2 54h	5 94c	4 57g	4 44f	4 84f	6 26d	4 79f	4 48f	3 27g	2 79f	1 71bcd	0 62b	0 28bc	0 10b
	V_9	1 28a	1 46cde	1 64c	1 97ef	2 15de	2 37i	4 27h	5 96c	4 36f	4 48g	5 10g	6 22c	4 09g	3 81f	3 01ef	1 41cd	1 00b	0 31bc	0 16ab
	V_{10}	1 38a	1 49bcd	1 74bc	1 93f	2 08f	2 29i	3 63i	5 69d	4 06g	4 18h	4 64h	6 00d	3 84h	3 63f	3 23e	1 01d	0 88b	0 28bc	0 21ab
Leaf area	V_1		45 7a	60 2a	145a	347a	401a	489a	646a	981a	1010a	1051a	1048a	990a	830b	597h	548e	529b		
	V_2		43 9a	58 2ab	144a	289b	389b	449b	602b	918b	966b	1044a	1031b	936b	878a	650c	507f	475e		
	V_3		41 4a	56 4ab	136b	256c	311d	376c	541c	838c	916c	981b	933c	836d	755g	615f	557d	532b		
	V_4		41 2a	55 2ab	134b	246d	321c	351d	478d	770d	971b	948c	901e	864c	795d	521i	415g	400h		
	V_5		40 5ab	53 1bc	134b	243d	293f	382c	417e	697e	845c	931d	921d	809e	764f	628e	577bc	441g		
	V_6		34 4bc	47 9cd	130b	195e	300e	351d	398g	649f	770d	866e	860f	836d	805c	672b	582ab	543a		
	V_7		33 3cd	47 7cd	130b	174f	278g	333e	406f	616g	736e	847f	842g	813e	777e	729a	504f	449f		
	V_8		29 9cd	43 9d	106c	155g	254h	307f	369h	573h	638f	819g	814h	776f	707h	605g	585a	475e	427c	
	V_9		27 9cd	42 1d	101c	125h	213i	238g	337i	533i	602g	781h	776i	747g	682i	635d	562d	485d	464a	
	V_{10}		27 3d	41 9d	100c	121h	155j	231h	308j	489j	569h	771i	752j	733h	711h	595h	574c	522c	435b	
Transpiration	V_1		18 35a	6 93b	6 62c	12 33a	5 20a	5 20b	4 44a	5 51c	9 03e	13 73ab	5 73c	3 15e	2 36e	1 84a	0 67d	0 38e		
	V_2		13 86b	6 88b	5 21d	11 88a	4 26d	6 62a	4 01b	11 65a	13 50b	13 65b	5 77c	2 80f	1 29f	0 79b	0 61d	0 27e		
	V_3		7 06d	8 34a	8 66a	8 58b	4 50c	4 08c	4 39a	8 64b	8 43f	12 26c	5 07d	4 28c	1 24f	0 68b	1 03a	0 68d		
	V_4		6 23f	5 91c	7 44b	7 06d	4 32d	2 54e	1 66d	4 58d	18 03a	10 88d	6 23b	3 84d	3 48c	0 61bc	0 38bd	0 87cd		
	V_5		10 19c	3 30i	6 77c	6 99d	4 70b	2 17e	0 51f	8 06b	12 09c	14 43a	5 75c	2 16g	3 90b	0 20c	1 03ad	0 83cd		
	V_6		9 79c	5 15d	6 46c	4 49e	3 54f	3 17d	0 56f	5 58c	9 19e	10 09e	4 52e	3 17e	0 55g	0 73b	0 55d	0 97c		
	V_7		6 24f	4 86e	2 00e	7 72c	3 89e	1 50fg	2 80c	3 96e	10 84d	11 16d	6 63a	3 69d	2 74d	1 97a	0 44bd	1 32b		
	V_8		9 76c	3 92h	5 45d	3 73f	2 80h	2 00ef	1 37de	4 68d	4 37g	7 93f	3 53f	3 61d	2 68d	1 86a	0 99cd	0 84cd	1 97a	
	V_9		4 65g	4 23g	1 51f	3 43f	2 70i	1 00g	1 24e	3 64e	9 17e	9 43e	5 56c	4 73b	5 38a	2 24a	1 05ad	1 76a	0 78b	
	V_{10}		7 12d	4 35f	0 41g	3 02g	3 00g	0 44h	1 27e	4 96cd	3 36h	12 31c	4 36e	6 34a	3 57c	0 86b	0 90a	1 27b	1 92a	

Methane flux was calculated by considering the change in methane concentrations inside the chamber, box volume at STP, paddy area covered by the chamber and time of sampling intervals using the equation of Parashar and Fisher (1998) The average of morning and evening fluxes were considered as the flux value for the day and expressed as mg m^{-2} h^{-1} Cumulative methane emission from different rice genotypes for the entire growth period was computed by the method of Naser et al (2007) by using the following formula

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

where R_i is the mean gas emission (mg m^{-2} day^{-1}), D_i is the number of days in the sampling interval and n is the number of sampling times Cumulative methane emission is presented as seasonal integrated flux (E_{sif}) and expressed in g m^{-2}

Measurement of morphophysiological parameters

Plant growth parameters such as tiller number (data not presented) and leaf area were measured at weekly intervals Total leaf area was measured by using portable [5] laser leaf area meter (CID model CI-203) Rate of transpiration (mmol H_2O m^{-2} s^{-1}) of intake leaf was measured at weekly interval (from day 7 after transplanting till [6] harvest) by an infrared gas analyzer (LI-6400 portable photosynthesis system, LI-COR) under ambient environmental conditions The middle portion of a fully expanded, healthy green second leaf from the top was used for measurement up to the preflowering stage, and the flag leaf was used from the panicle initiation stage Leaves were held in the chamber until values of transpiration were observed to be as constant as possible (steady state), which was rapid (3 ± 4 min) because of the similarity of environmental conditions of inside and outside the leaf chamber Leaves were kept at steady state for 1 min before measurements were taken

Evaluation of anatomical characteristics

For scanning electron microscopic (SEM) analysis, leaf sections were prepared from the middle portion of the of the flag leaf at panicle initiation stage Nodal sections of the stems were taken from about 15 cm above the ground surface Fresh leaf and stem samples of different rice cultivars were fixed and dehydrated following the method of Neinhuis and Edelmann (1996) After fixation and dehydration, samples were critical point dried, fixed to metal stubs with carbon adhesive tape, coated with [7] platinum by Auto Fine Coater (JFC-1600, JEOL, Japan) and examined in a scanning electron microscope (JSM-6390LV, JEOL) Observations and photographs with the SEM were made at 15 kV Four random fields from each sample were taken for the measurement of stomatal frequency (from the adaxial surface of the leaf sample) and expressed as number of stomata mm^{-2} For the measurement of the diameter of medullary cavity, stem sections were taken from the rice plants from about 15 cm above the ground surface Leaf sheaths were carefully removed and fine sections of the culm were examined under Stereo Microscope (Stemi 2000-C, ZEISS, Germany) [8] at 40× Observations were replicated for four times and diameters of medullary cavity were computed by using AXIOVISION LE DOCUMENTATION SOFTWARE (Germany) [9]

Statistical analysis

Measurements of different parameters at all the growth stages were replicated for four times The significance of the difference of different parameters among the cultivars was assessed by repeated measures ANOVA and subsequently by Duncan's multiple range test and differences are reported at $P < 0.05$, considering cultivars as source of variation Partial correlation of morphophysiological and anatomical parameters (means of all different growth stages) with mean CH_4 emission from different cultivars was analyzed The statistical analysis was conducted by using SPSS PACKAGE PROGRAMME (version 10 0)

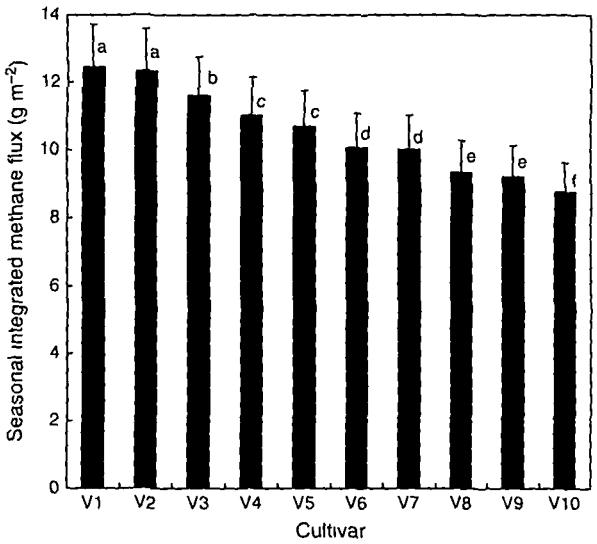


Fig 1 Seasonal integrated methane flux (E_{sif} g m^{-2}) of 10 rice cultivars (bars indicate standard error deviation values multiplied by 10) Bars with similar latter are not significantly different at $P < 0.05$ level by Duncan s multiple range test

Results

Measurement of CH_4 fluxes from 10 rice cultivars indicated significant cultivar differences in CH_4 emission (Table 1). Highest seasonal integrated CH_4 flux (E_{sif}) was recorded from plots grown cultivar Basmuthi (E_{sif} = 12.46 g m^{-2}) and lowest from Gitesh (E_{sif} = 8.74 g m^{-2}) (Fig. 1). The tested rice cultivars could be ranked into three groups based on their E_{sif} values (Fig. 1) as high- (cultivars: Basmuthi, Bogajoha and Choimora), medium- (cultivars: Rashmisali, Lalkalomdani, Mahsuri and Moniram) and low-CH_4-emitting cultivars (cultivars: Kushal, Prafulla and Gitesh). Despite the significant cultivar differences in CH_4 fluxes (Table 2), a similar seasonal pattern of CH_4 emission from all the rice cultivars was observed. In all the cases, CH_4 flux was initially very low and then increased with the advancing age of the rice plants. The rate of CH_4 emission declined after panicle initiation stage in all the cultivars and reduced to a negligible level at harvest (Table 1).

Significant variation in leaf area among the rice cultivars was noticed (Table 1). Highest leaf area was recorded in high-CH_4-emitting cultivar Basmuthi over the other cultivars. Low-CH_4-emitting varieties Gitesh and Prafulla recorded lower leaf area. Leaf area in all the

Table 2. Descriptive statistics of repeated measures of methane flux, leaf area and transpiration of 10 rice cultivars grown under wetland condition *Significant at the 0 01 level. DAT, days after transplanting

	Source	Sum of square	df	Mean square	F	Significance
Methane flux						
Test of within /subject effects (DAT)	DAT					
	Sphericity assumed	2185	18	121	5697	0 00*
	Lower bound	2185	1	2185	5697	0 00
	DAT × cultivar					
	Sphericity assumed	119	162	0 73	34 54	0 00
	Lower bound	119	9	13 24	34 54	0 00
	Error(DAT)					
	Sphericity assumed	7 66	360	0 021		
	Lower bound	7 66	20	0 383		
Test of between subject effects (cultivars)	*Intercept*	*6264*	*1*	*6264*	*68 420*	*0 00*
	Cultivar	86 1	9	9 6	104 5	0 00
	Error	1 83	20	0 092		
Leaf area						
Test of within subject effects (DAT)	DAT	$5\ 94 \times 10^7$	16	$3\ 71 \times 10^6$	$1\ 32 \times 10^6$	0 00
	Sphericity assumed	$5\ 94 \times 10^7$	1	$5\ 94 \times 10^7$	$1\ 32 \times 10^6$	0 00
	Lower bound					
	DAT × cultivar					
	Sphericity assumed	$4\ 60 \times 10^6$	144	31 960	11 330	0 00
	Lower bound	$4\ 60 \times 10^6$	9	$5\ 11 \times 10^5$	11 330	0 00
	Error(DAT)					
	Sphericity assumed	1354	480	2 82		
	Lower bound	1354	30	45 14		
Test of between subject effects (cultivars)	Intercept	$1\ 59 \times 10^8$	1	$1\ 59 \times 10^8$	$5\ 86 \times 10^5$	0 00
	Cultivar	$1\ 48 \times 10^6$	9	$1\ 64 \times 10^5$	609	0 00
	Error	8125	30	270 8		
Transpiration						
Test of within subject effects (DAT)	DAT	7106	16	444 12	5548	0 00
	Sphericity assumed	7106	1	7106	5548	0 00
	Lower bound					
	DAT × cultivar					
	Sphericity assumed	2333	144	16 2	202 4	0 00
	Lower bound	*2333*	*9*	*259 2*	*202 4*	*0 00*
	Error(DAT)					
Test of between subject effects (cultivars)	Sphericity assumed	8 42	480	5×10^{-5}		
	Lower bound	38 42	30	1 28		
	Intercept	14 430	1	14 430	37 620	0 00
	Cultivar	547	9	60 8	158 4	0 00
	Error	11 5	30	0 38		

cultivars increased gradually up to the panicle initiation stage and declined thereafter

Significant differences in the size of the medullary cavity of different rice cultivars were observed (Table 3, Fig 2) High-methane emitting cultivars viz Basmuthi and Bogajoha recorded greater size of medullary cavity than lower emitting cultivars Gitesh and Prafulla Significant positive correlation was recorded between methane emission and size of medullary cavity (Table 4) Higher stomatal frequencies were exhibited by Basmuthi and Bogajoha, whereas Prafulla and Gitesh showed lower stomatal frequencies (Table 3, Fig 3) Transpirational rates of the cultivars were recorded at weekly interval Significant cultivar differences were observed in the rate of transpiration at different growth stages of the crop High- and medium CH_4-emitting cultivars recorded higher rate of transpiration compared with low-emitting varieties (Table 1) Water level of the experimental field was recorded during the time of methane sampling and presented in Fig 5

Discussion

In the present investigation, significant differences in the size of the medullary cavity of the rice cultivars were observed (Table 3, Fig 2) High-methane-emitting cultivars recorded significantly greater size of medullary cavity compared with medium- and low emitting ones

Table 3 Variation in diameter of medullary cavity and stomatal frequency of 10 rice cultivars grown under wetland condition In each column means with the similar letters are not significantly different at $P < 0.05$ level by Duncan's multiple range test Values within parenthesis indicate standard error deviation

Cultivar	Diameter of medullary cavity (mm)	Stomatal frequency (number of stomata mm^{-2})
Basmuthi	6 93 (±0 06)a	736 (±20)a
Bogajoha	7 21 (±0 21)a	637 (±33)b
Choimora	6 19 (±0 15)b	617 (±20)b
Rashmisali	6 39 (±0 07)b	577 (±20)b
Lalkalomdani	6 01 (±0 27)b	597 (±23)b
Mahsuri	6 17 (±0 07)b	498 (±20)c
Moniram	5 99 (±0 11)b	378 (±20)de
Kushal	5 98 (±0 24)b	398 (±33)d
Prafulla	5 41 (±0 09)c	338 (±20)de
Gitesh	3 92 (±0 05)d	318 (±33)e

Methane concentrations in the medullary cavities of rice plants are reported to be about 2900 times higher than that of ambient air (Nouchi et al 1990) Therefore, it is possible that methane may diffuse and move upward through the shoots through the internal air spaces along concentration gradients Because methane emission is diffusion-controlled process, it is logical to hypothesize that larger size of the medullary cavities recorded in the cultivar Basmuthi and Bogajoha may increase the cross-sectional area of the methane diffusion pathway

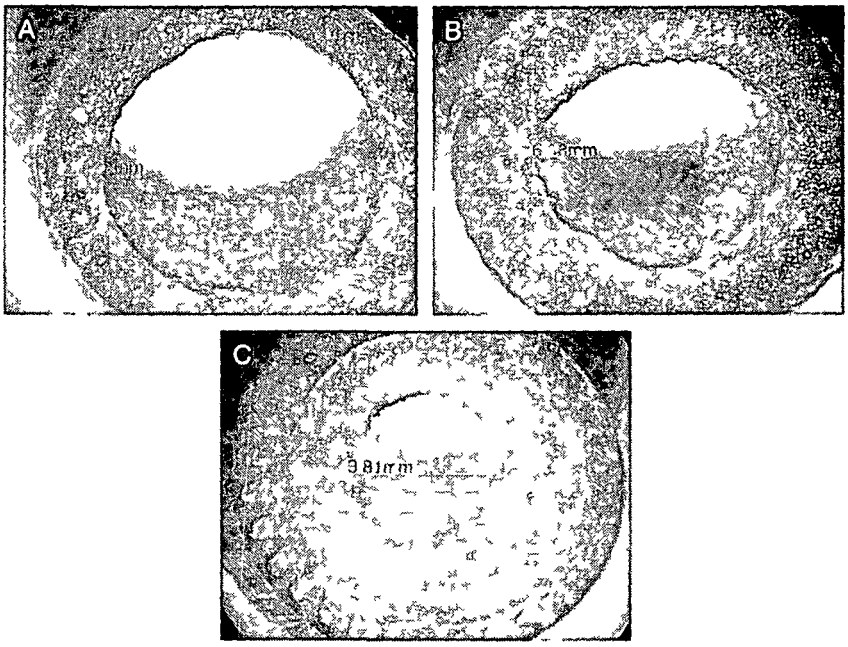


Fig 2 Micrographs of medullary cavity of (A) Basmuthi (high methane emitting cultivar) (B) Lalkalomdani (medium methane emitting cultivar) and (C) Gitesh (low methane emitting cultivar)

Table 4 Partial correlations of morphophysiological and anatomical characteristics of rice cultivars with methane emission *Correlation is significant at the 0 01 level

Parameters	Methane emission
Leaf area	0 98*
Tiller number	0 85*
Diameter of medullary cavity	0 84*
Stomatal frequency	0 95*
Transpiration	0 99*

On the other hand, smaller medullary cavities of Prafulla and Gitesh may restrict the methane flow by reducing the cross-sectional area This may be one of the reasons of higher methane emission from the cultivars Basmuthi and Bogajoha This finding suggests that the wide variation in methane emission among the rice cultivars may be associated with the anatomical features of the medullary cavity A positive correlation between the seasonal integrated methane flux and the size of medullary cavity was observed (Table 3) Our assumption on the role of medullary cavity in methane emission may be supported by the report of Yao et al (2000) that methane transport was correlated with intercellular volume of stem

Numerous stomata were detected at the adaxial surface of rice leaves SEM showed higher stomatal frequencies in the leaves of high-methane-emitting cultivars (Fig 3) Both methane emission and seasonal integrated methane flux were positively correlated with stomatal frequency (Table 4) The stomata of leaf blade may be one of the release sites of methane into the atmosphere Positive influence of leaf area and tiller number on methane emission was reported from this laboratory (Das and Baruah 2008, Gogoi et al 2005) In the present investigation also, high-methane-emitting cultivars recorded higher tiller number compared with low-methane-emitting varieties (data not presented) It may be hypothesized that if leaf stomata is one of the release sites of methane, higher tiller number and leaf area with higher stomatal frequency provide more cross-sectional area for release site of methane from the plant body to the atmosphere Other workers also reported that before shoot elongation, about 50% of the methane is released from leaf blades (Neue et al 1997) Although micropores, present in the basal portion of leaf sheath, were described as the main site of methane release by Nouchi et al (1990), it was also pointed out by them that the micropores, surrounded by sclerenchyma, are not linked to the lysigenous intercellular space Moreover, the presence of micropores in the leaf sheath was not con firmed by other workers (Butterbach-Bahl et al 2000) and such differences in findings might be attributed because

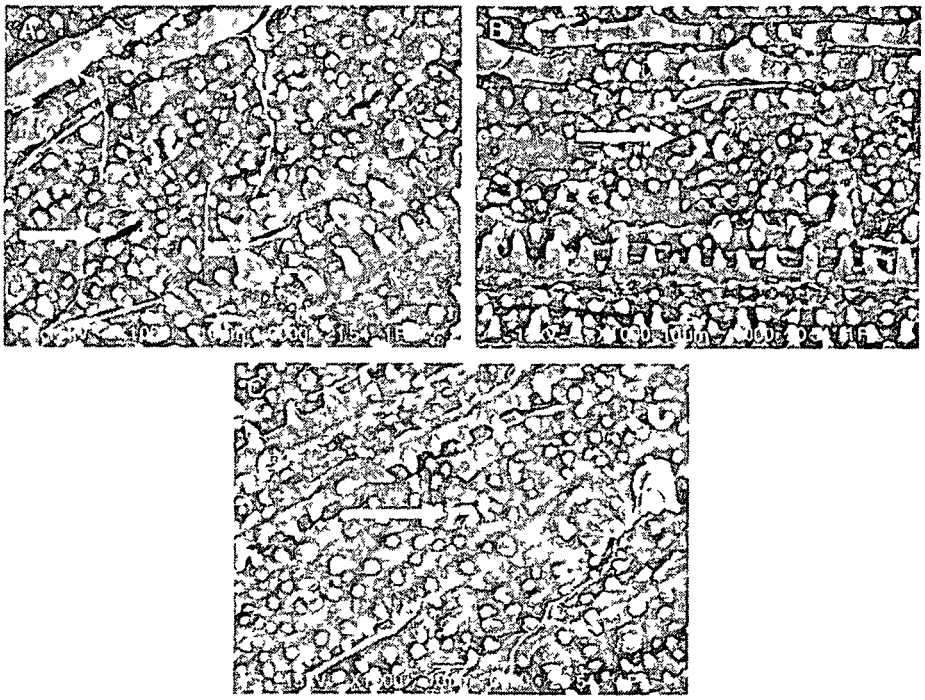


Fig 3 Scanning electron micrographs of stomata on the adaxial leaf surfaces of (A) Basmuthi (high-methane emitting cultivar) (B) Lalkalomdani (medium methane emitting cultivar) and (C) Gitesh (low methane emitting cultivar) Arrows point to the stomata

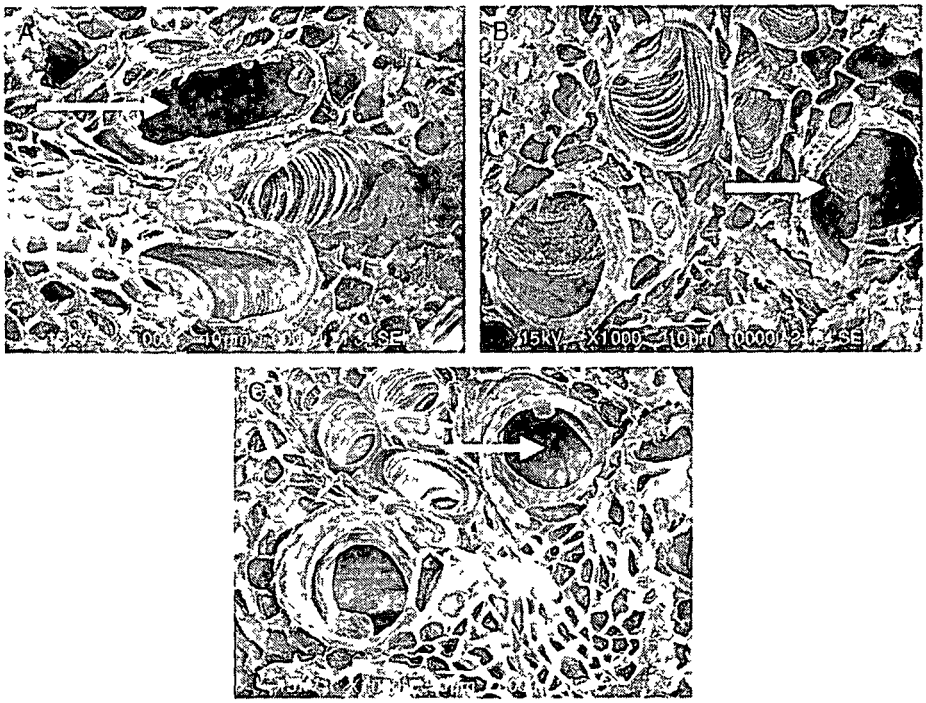
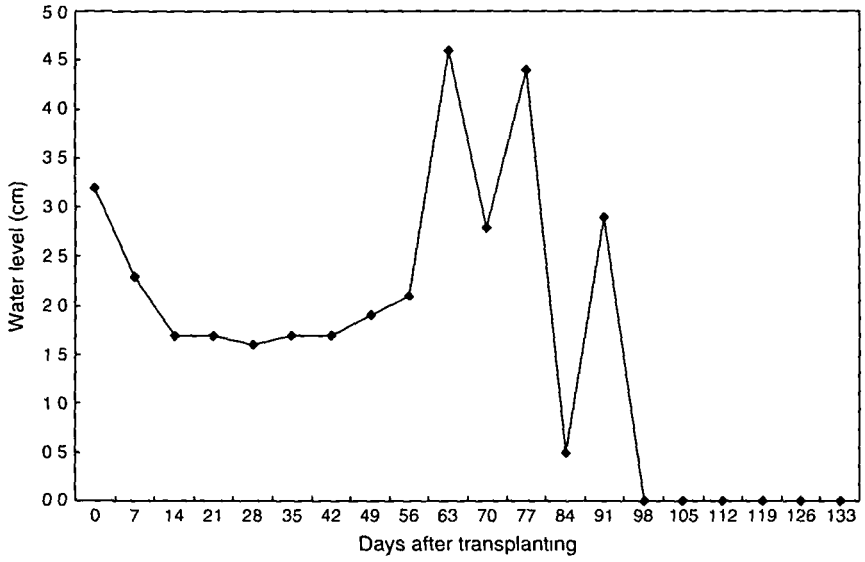


Fig 4 Scanning electron micrographs of vascular bundles of (A) Basmuthi (high-methane-emitting cultivar) (B) Lalkalomdani (medium-methane-
[14] emitting cultivar) and (C) Gitesh (low-methane-emitting cultivar) Arrows point to the xylem

of the differences in cultivars (Wang et al 1997) The intercellulars located between the epithelial cells and the closely related to the leaf sheath stomata may have a crucial role in plant-mediated methane transport (Butterbach-Bahl et al 2000), and a link of the stomata with the lacunae through these intercellulars is logically assumed Stomata of the leaf sheaths are suggested to be the main site of methane release (Butterbach-Bahl et al 2000) Similar mechanism may operate in the leaf blade also, which may explain the close relationship among



[15] Fig 5. Water level (cm) of the experimental field during the experimental period

methane emission, leaf area and stomatal frequency observed in our study

Significant positive correlation was recorded among transpiration, methane emission and seasonal integrated methane flux (Table 4) in the rice varieties High-methane-emitting cultivars exhibited higher transpirational rate than the low-emitting varieties (Table 1) Allen et al (2003) recorded that highest CH_4 efflux coincides with increased transpirational rate indicating that soil water flow to the roots deliver more dissolved CH_4 to the rice plant during periods of rapid transpiration Diel rates of CH_4 emissions were also found to be linked with the transpiration-induced bulk flow (Chanton et al 1997) However, by using SEM, we were unable to show the difference in the distribution and anatomy of xylem in the node of rice stem (Fig 4) From the data recorded on stomatal frequency, leaf area and transpirational rate, it may be hypothesized that at least a small fraction of methane may be released into the environment because of transpiration-induced bulk flow, although methane is transported within the rice plant predominantly through molecular diffusion It may be noted that all the traditional rice cultivars examined in this investigation recorded higher leaf area and tiller number with higher transpirational rate and bigger medullary cavity, emitted more methane compared with the high-yielding improved cultivars Although it is difficult to specify the primary factor for high methane emission, it may be assumed that all these factors collectively regulate methane emission from rice plant However, as discussed above, the transport mechanism of methane to stomata from the lacunae through intercellulars is not well understood This intercellular mechanism must be described with more sophisticated methodologies, e g use of radiotracer techniques for clear understanding of plant-mediated methane transport The findings of the present study might open up new areas for further research on methane transport

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References

Allen LH Jr, Albrecht SL, Colón-Guasp W, Covell SA, Baker JT, Pan D, Boote KJ (2003) Methane emissions of rice increased by elevated carbon dioxide and temperature J Environ Qual 32 1978–1991

Aulakh MS, Bodenbender J, Wassmann R, Rennenberg H (2000) Methane transport capacity of rice plants I Influence of methane concentration and growth stage analyzed with an automated system Nutr Cycl Agroecosystem 58 357–366

Butterbach-Bahl K, Papen H, Rennenberg H (2000) Scanning electron microscopy analysis of the aerenchyma in two rice cultivars Phyton 40 43–55

Chanton JP, Whiting GJ, Blair NE, Lindau CW, Bollich PK (1997) Methane emission from rice stable isotopes, diurnal variations, and CO_2 exchange Global Biogeochem Cycl 11 15–27

Cheng W, Yagi K, Sakai H, Kobayashi K (2006) Effects of elevated atmospheric CO_2 concentrations on CH_4 and N_2O emission from rice soil an experiment in controlled-environment chambers Biogeochemistry 77 351–373

Das K, Baruah KK (2008) A comparison of growth and photosynthetic characteristics of two improved rice cultivars on methane emission from rainfed agroecosystem of east India Agric Ecosyst Environ 124 105–113

Gogoi N, Baruah KK, Gogoi B, Gupta PK (2005) Methane emission characteristics and its relations with plant and soil parameters under irrigated rice ecosystem of northeast Chemosphere 59 1677–1684

Hosono T, Nouchi I (1997) The dependence of methane transport in rice plants on the root zone temperature Plant Soil 191 233–240

IPCC (1994) Climate Change 1994 In Houghton JT, Mera Filho LG, Bruce J, Lee H, Callander BA, Hailes EF, Marris N, Maskel K (eds) Radiative Forcing of Climate Change and an Estimation the IPCC IS92 Emission Scenarios Cambridge University Press, New York [10]

IPCC (2007) Climate Change 2007 The Physical Science Basis Summary for Policymakers Intergovernmental Panel on Climate Change, Geneva, Switzerland

Jimenez J, Lal R (2006) Mechanism of sequestration in soils of Latin America Crit Rev Plant Sci 25 337–365

Keppler F, Hamilton JTG, Brab M, Rockmann T (2006) Methane emissions from terrestrial plants under aerobic conditions Nature 439 187–191

Keppler F, Rockmann T (2007) Methane, plants and climate change Sci Am 296 40–45

Naser HM, Nagata O, Tamura S, Hatano R (2007) Methane emission from five paddy with different amounts of rice straw application in Hokkaido, Japan Soil Sci Plant Nutr 95–101 [11]

Neinhuis C, Edelmann HG (1996) Methanol as a rapid fixative for the investigation of plant surfaces by SEM J Microsc 184 14–16

Neue HU, Wassmann R, Kludze HK, Bujun W, Lantin RS (1997) Factors and processes controlling methane emissions from rice fields Nutr Cycl Agroecosystem 49 111–117

Nouchi I, Mariko S, Aoki K (1990) Mechanism of methane transport from the rhizosphere to the atmosphere through rice plants Plant Physiol 94 59–66

Parashar DC, Fisher FM Jr (1998) Methane from irrigated rice cultivation In Sharma C, Mitra AP (eds) Global Environment Chemistry Narosa Publishing House, New Delhi, India, pp 77–93 [12]

Schutz H, Seiler W, Conrad R (1989) Processes involved in formation and emission of methane in rice paddies Biogeochemistry 7 33–53

Wang B, Neue HU, Samonte HP (1997) Role of rice in mediating methane emission Plant Soil 189 107–115

Wassmann R, Neue HU, Alberto MCR, Lantin RS, Bueno C, Llenaresas D, Arah JRM, Papen H, Seiler W, Rennenberg H (1996) Flux and pools of methane in wetland rice soils with varying organic inputs Environ Monit Assess 42 163–173

Yagi K, Tsuruta H, Kanda K, Minami K (1996) Effect of water management on methane emission from a Japanese rice paddy field automated methane monitoring Global Biogeochem Cycl 10 255–267 13

Yao H, Yagi K, Nouchi I (2000) Importance of physical plant properties on methane transport through several rice cultivars Plant Soil 222 83–93

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