UNIVERSITY OF SOUTHERN QUEENSLAND

FIELD EVALUATION AND MODELLING OF WATER AND NITROGEN MANAGEMENT STRATEGIES IN TROPICAL LOWLAND RICE–BASED PRODUCTION SYSTEMS

A Dissertation Submitted by

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M.Agr.Sc.

for the award of

Doctor of Philosophy

2010

Dedicated to my beloved parents:
Amaq Sium & Sindawati
My wife: Sri Marliana Setianingsih
and my children: Syarifana ‘Aisyah Suriadi
Ahmad ‘Aliqari Suriadi
‘Athaana Fathimah Suriadi
Ahmad ‘Alifirdaus Suriadi
Ahmad ‘Alikaustar Suriadi

ABSTRACT

With increased competition for land and water from the urban and industrial sectors and high population growth in the major rice producing nations, the possibility for expanding area under rice-based farming systems is limited. Use of marginal, coarse-textured soils of high permeability has increased over time for production of both upland and lowland irrigated rice to meet the demand for food and fibre to support growing populations. In irrigated rice fields with fine-textured soil, leaching losses of N are usually low because of low permeability. However, in highly permeable coarse-textured soils, the losses of N through leaching of nitrate-N (NO_3-N) and other processes can be substantial. Information on water and nitrogen dynamics for rice crop on coarse-textures soils is limited. Since models can provide an insight of the interrelationships between various components of a complex system, the overall aim of this research is to improve crop growth simulation capability for a range of water and nitrogen management strategies for rice-based cropping systems in tropical environment. The specific objectives of this research project are:

1. to examine variation in water use productivity in lowland rice-based cropping systems without significant effects on yield;
2. to explore the nitrogen dynamics in rice-rice-legume crop sequences on a typical coarse-textured soil of lowland cropping systems in the tropics;
3. to calibrate and validate a farming system model that can be used to simulate growth, yield, nitrogen uptake, nitrogen and water dynamics in the above rice-based cropping systems.

To achieve these objectives, field experiments were conducted at the Research Station of Assessment Institute for Agricultural Technology (BPTP) NTB Lombok Indonesia (08°35′N, 116°13′E, 150 m elevation) on a sandy loam soil using rice-rice-legume crop rotation over two years (2007-2009). The experiment was laid out in a randomised split-plot design with water management treatments (continuously submerged and alternate submerged and non-submerged, hereafter referred to as CS and ASNS, respectively) as main plot and N-fertiliser rates (0, 70 and 140 kg N ha^{-1}) treatments as subplot with three replications. Plant and soil samples were collected at four main phenological stages during rice growth period (tillering, panicle initiation, flowering and harvesting). Plant samples were measured for dry biomass and total-N. Soil samples were taken within 0-100 cm depth from four soil layers (0-20, 20-40, 40-70 and 70-100 cm) and each sample was analysed for ammonium-N (NH_4-N), NO_3-N, total-N, and organic carbon (OC). Legumes (peanut and soybean) were sown immediately following the second rice crop in each calendar year. The experimental design was similar to rice by replacing CS and ASNS treatments with peanut and soybean, respectively and reducing N-fertiliser application rates to 0, 12 and 24 kg N ha^{-1}. Crop and soil samples were collected at three main phenological stages of legume (maximum vegetative, flowering and harvesting) and analysed as for the rice crop. Data of field experiment were used to parameterise, calibrate and validate the APSIM-Oryza model.

The results indicated that biomass, yield and N-uptake of rice were not significantly different between ASNS and CS. Any increase in yield and N-uptake was largely due to increased N-fertiliser application. Average irrigation water saved with ASNS varied in the range of 36% to 44% when compared with CS irrigation treatment. Furthermore, average water productivity in the ASNS treatment was 52% higher than for the CS irrigation treatment. Considering these results as typical for well-drained soils with deep ground water tables, ASNS practices can make considerable water-saving without substantial yield reduction in irrigated lowlands of eastern Indonesia. Furthermore, yield of both peanut and soybean crops following the second rice crop were not affected by N fertiliser rates. The implication of this study is that the farmers should consider ASNS as a water saving technology in this region of study and should not consider applying N-fertiliser for peanut and soybean crops when it follows the second rice crop.

Seasonal variation in soil nitrogen and carbon in lowland rice-based cropping systems indicated significant effects of N-fertiliser treatments on NH_4-N and NO_3-N concentration in soil, but only on a few occasions for irrigation treatments. For example, NO_3-N concentration in soil under ASNS treatment was higher than the CS treatment during panicle initiation and flowering stages in the later part of the rice growing seasons. Since rice prefers ammonium over the nitrate form of N, increased nitrate concentration during the periods of non-submergence in ASNS irrigation treatment could have adversely affected N-uptake by rice. However, no significant difference in N-uptake was observed between CS and ASNS possibly because of the small magnitude of NO_3-N concentration differences between these irrigation treatments. . Since floodwater is another useful source of N for the rice crop, measurements in this experiment showed NH_4-N concentration in soil and floodwater to be mostly higher than NO_3-N concentration that allowed adequate N-uptake. Organic carbon as an indicator of soil organic matter and overall soil fertility was not affected by irrigation and N fertiliser treatments during the experiment.

During the legume season, increased rates of N-fertiliser application increased NH_4-N and NO_3-N concentration at various soil depths throughout crop growth. Increased concentration of available forms of N as a result of increased level of N-fertiliser applied to legumes decreased the number and weight of root nodules on some occasions. Since increased N-fertiliser application increased N-uptake and seed N-uptake but not yield, N-fertiliser application is not recommended for legumes in this region on the basis of improved crop quality.

The APSIM-Oryza model was mostly able to capture the variable effects of water and N management strategies on crop growth, nitrogen and carbon dynamic in soil, and the dynamics of ponded water depth under anaerobic and aerobic soil conditions in the rice-rice-legume crop sequence as practiced in the tropical region of eastern Indonesia. The model satisfactorily simulated crop variables such as biomass, yield, leaf area index (LAI) and N-uptake. The model also satisfactorily simulated the variation of water depth during rice growth period. However, the simulation of N dynamics and floodwater (ponding) in the ASNS irrigation treatment need further improvement. The APSIM-Oryza model provided an operational and a promising modelling framework to test future cropping practices and improve making farm decisions to develop more sustainable and effective lowland rice-based farming systems. This thesis has produced a dataset to calibrate and evaluate the model performance by capturing the dynamics of various forms of nitrogen and daily ponded water depth for water limited rice-based cropping systems. More extensive field experimental testing is needed to increase confidence with the widespread use of this model.

CERTIFICATION OF DISSERTATION

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

Ahmad Suriadi, Candidate Date

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ACKNOWLEDGEMENTS

It is not possible to complete this dissertation without genuine support and generous help from a number of people to whom I wish to express my sincere gratitude.

I would like to express my sincere thanks to my principal supervisor Dr. Rabi Misra and associate supervisor Dr. Yahya Abawi for their invaluable guidance, patience and persistence in helping me to complete this dissertation. Without their support, it would not be possible for me to complete this research project. Their guidance, sacrifice and help will be remembered during the rest of my life. I would also like to thank Mr. Don Gaydon (CSIRO St. Lucia Brisbane) for his guidance with the use of APSIM-Oryza model. Without his help, it would not have been possible to run the APSIM model in this project.

Without the financial support from the Australian Centre for International Agricultural Research (ACIAR) who offered me the Postgraduate Scholarship, I would not be able to undertake this study.

Thanks to Dr. Dwi Praptomo Sudjatmiko, MS., Head of BPTPNTB Lombok Indonesia, for giving permission to conduct field experiments within the Research Station. Sincere thanks are also due to the BPTPNTB staff, Mr Yunus and Mr Abdul Gaffar, for their kind support and assistance throughout the field experiment.

My thanks go to all the staff and research students of the Faculty of Engineering & Surveying and staff of the Office of Research and Higher Degrees who helped me in various ways during my stay at the University of Southern Queensland. I also cannot forget my friends and their families, who are outside the university, for their kindness and support during my stay in Toowoomba. Thanks to Dr. Sunil Dutta for his help with statistical analysis.

I am as ever, especially indebted to my parents, brothers and sisters for their love and support throughout my life. Finally, my sincere thanks go to my wife Sri Marliana Setianingsih and my children, Syarifana ‘Aisyah Suriadi, Ahmad Aliqari Suriadi, ‘Athaana Fathimah Suriadi and Ahmad Alifirdaus Suriadi for their love, patience and support throughout this study. Lastly, I offer my regards and blessings to all of those who supported me in any respect during the completion of this study.

TABLE OF CONTENTS

LIST OF FIGURES

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

LIST OF TABLES

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

CHAPTER I

Introduction

1. 1 Background

Rice is the staple food of almost half the earth's population that is mostly concentrated in Asia, consisting of 135 million hectares of harvested area with 55% of which is irrigated (Calpe, 2001; FAO, 1999; Kennedy et al., 2002). It is predicted that the population of the world will increase and half of these will be dependent on rice. By 2015, sufficient rice will need to be produced to feed 4 billion people (Greenland, 1997) with the demand for rice is projected to increase from 571.9 million tonnes in 2001 to 771.1 million tonnes in 2030 (FAO, 2003). Furthermore, the harvested area for rice has decreased globally by about 3.4 million hectares from 1999 to 2005 (FAOSTAT, 2005). The possibility for expanding area under rice-based farming systems will be limited within the major rice producing nations due to increased competition for land and water from the urban and industrial sectors where the population growth is concentrated (Nguyen, 2006; Tuong and Bhuiyan, 1994). Therefore, increasing the productivity of rice will continue to be a major challenge to meet the demand of increasing population with limited area of arable land.

Most of the paddy soils around the world are fine textured soils (clay soils) with low permeability (percolation rate). However, with increasing demand on food and fibre to support the growing population, coarse-textured soils with high permeability are increasingly used in these regions to grow both upland and lowland irrigated rice (Aulakh and Bijay-Singh, 1997; Aulakh and Pasricha, 1997). It is difficult to maintain continuous flooding conditions for lowland rice in coarse textured soils due to high percolation rates requiring frequent irrigation. Improved planning and management of water resources within the agricultural sector is a high national and global priority in major rice producing countries where rice production needs to increase by 70% over the current production level by 2025 (Tuong and Bhuiyan, 1999).

Irrigated rice accounts for 75% of rice producing area in Asia because rice yield is higher under irrigated than under rainfed conditions (Maclean et al., 2002).

Consequently, irrigation management is a critical factor in determining crop production within Asia's most important agro-ecosystem (rice) because limited-irrigation can reduce yield and over-irrigation can result in a waste of water. Over-irrigation can reduce profit with increased cost of water associated with over-irrigation and increases the pollution risk through nutrients loss via leaching and runoff (Aboitiz et al., 1986; Guerra et al., 1998). Research on water management is needed to save water and produce more rice with less water in irrigated production systems (Guerra et al., 1998) and to increase the efficient use of nutrients, especially nitrogen. Understanding the fate of soil water and nitrogen (N) is essential for improving crop yield and optimizing the management of water and N in rice-based cropping systems.

Nitrogen fertilizer is the most important nutrient in rice production systems and has contributed immensely to the current level of productivity. Furthermore, N fertilizer will play a key role in future rice production as it accounts for 67% of total fertilizer applied to rice worldwide (Vlek and Byrens, 1986). Efficient management of N is important for both economical and environmental reasons (Powlson, 1993; Jervis, 1996). In flooded rice crop, only 20-40% of the applied N is used (Vlek and Byrens, 1986; Cassman et al., 1993, 1996). The main reasons for such low N fertiliser efficiency in flooded rice are due to N losses by leaching, volatilization and coupled nitrification-denitrification processes. If both nitrogen and irrigation are not correctly managed, significant amount of nitrogen can be leached below the root zone (Vlek and Byrens, 1986) reducing yield due to inadequate nitrogen supply to the crop. Therefore, it is important to optimise N and irrigation management in rice-based cropping systems because fertiliser prices have continued to increase, water is becoming scarce and environmental pollution needs to be avoided (Ladha et al., 2005). Thus, there is a need to identify management systems that help determine the fate of applied fertilizer-N and quantify the dynamics and losses of N at field, farm and regional scales.

Rice-based cropping systems which include a legume crop are important for maintaining soil fertility as legumes are capable of fixing atmospheric N which reduces the need for increased use of N-fertilizer and protects the environment from N losses. The rice-rice-legume cropping system with the occasional substitution of legume with other crops is a commonly practiced farming system in lowland of Indonesia and other parts of the world such as Bangladesh, Southern China, Myanmar, Philippines and Vietnam (Kueneman, 2006). Legumes are a potential source of both nitrogen and carbon (organic matter) in soil as they are able to enhance soil fertility by supplying N to the succeeding crop and improving soil's physical properties. In tropical regions, the dynamics of nitrogen released from legume crop residues have not received much attention.

The transformation and distribution of N in a ponded rice field and in the dryland condition during the legume crop are very different, which makes it difficult to accurately assess the effects of applied fertilizer-N on the productivity of the rotated crop within the cropping system. Although various forms of N and its distribution can be measured in field experiment, these samplings and measurements are labour-intensive and expensive. To overcome the need for these measurements and to design optimal management systems, simulation modelling techniques have been suggested as an alternative for the analysis of system performance on different soils and climate types (Godwin and Jones, 1991; Godwin and Singh, 1998; Ritchie et al., 1998; Jones et al., 2003). Another drawback of field experiments is that experiments are conducted at a small plot scale, but experimental results are extrapolated to the whole region. Such recommendations may not account for soil and weather variability across various locations within a region (Matthew et al., 2000). In these situations, crop simulation models have some advantage as these can synthesize much of the information from various experiments at diverse locations and provide a way to extrapolate this information to other regions of interest, with different soil and climatic characteristics (Matthew et al., 2000). Simulation of various crop and fertilizer management strategies using such models can also lead to better fertiliser decision-making (Godwin and Jones, 1991; Paz et al., 1999).

Cropping system models integrate data management and knowledge of soil, plant and atmospheric systems to allow simulation of a cropping system over a wide range of environments and management practices (Larson et al., 1996; Pala et al., 1996; Cavero et al., 1998; Hunt and Boote, 1998; Alves and Nortcliff, 2000; Mailhol et al., 2001). This makes them valuable tools for agricultural professionals around the world (Bouman et al., 1996; Jones et al., 2003). Development and evaluation of models require all of the aforementioned types of data together with additional data such as time-series data on crop development, soil moisture, and soil nutrients as well as yield and yield components (Hunt and Boote, 1998). For adaptation and application to different cropping systems, these models need to be calibrated and validated for their performance in the agroclimate of the region of interest.

Considerable efforts and progress have been made with the study of rice production systems resulting in the development of several simulation models of rice crop (Aggarwal et al., 1997; Bouman et al., 2001; Fukai et al., 1995; Godwin and Jones, 1991; Horie et al., 1992; McMennamy and O'Toole, 1983). ORYZA2000 is one of the most advanced simulation models for rice developed at the International Rice Research Institute in the Philippines with new features which include various options of irrigation and nitrogen management in rice. In addition, the ORYZA2000 model has been intensively tested (Bouman et al., 2001). However, The ORYZA2000 model is based for a single season of rice. The model cannot simulate growth of multiple crops required for a rice-based crop sequence (cropping system). Furthermore, the model does not simulate the residual nitrogen and water that may be carried over from one crop to the next in a sequence of crops. In addition, there is an increased need for the modelling capability to simulate rice-based cropping systems in Asia. Such a system capability will allow investigation of residual nitrogen, crop sequence, intercropping, crop residue management and soil and water management.

A cropping system model, APSIM (Agricultural Production System Simulator), developed in Australia is able to predict crop growth, yield, nitrogen uptake, nitrogen dynamics in soil and rotation effects on crop residue over a long period (Keating et al., 2003). System-related processes are available to any crop module from APSIM's infrastructure and generic crop library (Wang et al., 2003). However, APSIM is based on the dryland farming system that does not include the capability to model lowland rice crop preferred in tropical regions. Lowland rice (Paddy) is a complex cropping situation as it involves transformation and leaching of N between the water-ponded surface and other oxidized and reduced soil layers. Currently the model is lacking the capability to simulate these processes (Keating et al., 2003; Zhang et al., 2007). In this situation, the versatility of the model can be increased if it is able to simulate the processes of nitrogen dynamics in lowland rice and is able to correctly simulate the growth and productivity of rice-rice-legume rotation systems of Asia.

The APSIM-Oryza was developed in 2004 (Zhang et al., 2004) available at: http://www.regional.org.au/au/asa/2004/poster/2/8/1212_zhang.htm), aiming to combine the strength of rice physiology simulation in ORYZA2000 (Bouman et al., 2001) and the system capability of APSIM to simulate long-term rice-based agricultural production system. The model's performance to simulate continuous long-term rice-based system under different nitrogen and other management practices for several rice varieties was tested against comprehensive datasets from Philippines (Zhang et al., 2004) and Korea (Zhang et al., 2007). The testing had found the previous version of APSIM-Oryza cannot simulate nitrogen dynamics in the soil profile over seasons and therefore developing a dynamic soil nitrogen module for paddy soils was recommended (Zhang et al., 2007). The results led to the development of new or modified modules (APSIM-Pond and APSIM-SoilN) to simulate nitrogen dynamics in pond water and paddy soil by Gaydon et al in 2009 based on CERES-rice (Godwin and Singh, 1998). However, so far the newly-developed APSIM-Pond and APSIM-SoilN and their integration with APSIM-Oryza remain untested especially in tropical conditions. The testing is crucially important to apply the model to explore optimal water and nitrogen management in the rice-rice-legume cropping system in eastern Indonesia.

1. 2 Research hypotheses:

The research hypotheses proposed for this study are as follows:

1. Water use productivity in rice-rice-legume crop sequences in lowland farming system of the tropical environment can be increased without significantly decreasing yield through improved water management.
2. The dynamic aspects of nitrogen in soil-plant system for a rice-based cropping system can be quantified through a series of field experiments.
3. Simulation models can be used to predict crop growth and development, yield, nitrogen uptake, nitrogen and water dynamics for a sequence of crops in lowland rice-based cropping systems.

1. 3 Overall research aim

The overall aim of this research is to improve crop growth simulation capability for a range of nitrogen and water management strategies for rice-based cropping systems in tropical environments. The research involved experiments and field measurements to determine the influences of nitrogen and water management on continuous rice-rice-legume crop sequences for at least 2 years. A whole–farm model suitable for a rice-based production system was calibrated and validated which can be used to explore a range of fertiliser and water management responses to increase the sustainability of tropical rice-based production systems.

1. 4 Objectives

The specific objectives of this research project are:

1. to examine variation in water use productivity within the above rice-rice-legume crop sequence without significant effects on yield;
2. to explore nitrogen dynamics in rice-rice-legume crop sequences on a typical coarse-textured soil of lowland farming systems in the tropics;
3. to calibrate and validate a farming system model that can be used to simulate growth, yield, nitrogen uptake, nitrogen and water dynamics in the above rice-based cropping system.

1. 5 Outcomes of the study

The main outcomes from this study include:

1. Strategies and recommendations for nitrogen and water management in rice-rice-legume crop sequence as practised in coarse-textured soils of lowland farming systems in a tropical climate;

2. A calibrated and validated farming system model and associated program useful for rice-based cropping systems in the lowland farming systems.

1. 6 Structure of the Thesis

This thesis contains eight chapters including this chapter. A brief summary of each chapter is outlined below.

Chapter 1 consists of a brief outline of the background to this research, research hypotheses and the overall research aim. It also includes the objective and outcomes of the study followed by a brief overview of the dissertation structure.

Chapter 2 presents a comprehensive literature review related to the broad aims of the research. This chapter includes a brief overview of the lowland rice-based cropping systems in the tropical environment, typical aspects of nitrogen dynamics highlighting various processes of the nitrogen cycle in both aerobic and anaerobic conditions and water management practices. This chapter also highlights the importance of modelling rice-based cropping systems. All these are essential for improving the effectiveness of nitrogen fertilizer and irrigation water management and for modelling management of rice-based cropping systems in tropical environment.

Chapter 3 includes an outline of the field experimental design and its layout, management of crop, fertiliser and irrigation treatments and the details of sampling and measurements for the collection of all data. The field experiment was conducted for a rice-rice-legume crop sequence over two years that included peanut and soybean as legumes. Data collected in this chapter were also used for calibration and validation of APSIM-Oryza model.

Chapter 4 details the effects of irrigation treatments (the traditional practice of continuously submerged compared (CS) water regime with alternately submerged and non-submerged (ASNS) water regime) and N-fertilizer treatments on growth and yield of rice and discusses their implications.

Chapter 5 includes the nitrogen dynamics for various water and N fertilizer treatments during two years rice-rice-legume crop sequence. The differences in temporal variation in various forms of soil nitrogen under flooded and ASNS conditions as affected by irrigation regimes and its implication to ammonium and nitrate nutrition of the crop are discussed in this chapter.

Chapter 6 discusses the performance of legume crop in relation to the nitrogen dynamics in soil during the dry season that follows two seasons of lowland rice in tropical climate. Legumes (peanut and soybean) are commonly planted as cash crops which influence various forms of N in soil (NO_3-N and NH_4-N) and their performance in relation to fertilizer-N management is explored in this chapter.

Chapter 7 tests the performance of the APSIM-Oryza model to simulate lowland rice-based cropping systems as practiced in the tropics. In this chapter, the capability of APSIM-Oryza to simulate floodwater dynamics in CS and ASNS water treatments, growth and development of rice, peanut and soybean, and variation in various forms of N (NH_4-N and NO_3-N) and organic carbon in soil is evaluated along with the effects of various N fertiliser rates. Description and overview of the model are briefly outlined to include crop modules (rice, peanut and soybean), SoilWat, SoilN and Pond modules. Parameterisation of the model for rice-rice-peanut and rice-rice-soybean crop sequences are discussed here along with the features of the new module of APSIM-Pond (developed elsewhere). Calibration and validation of the model using two years of field experimental data for rice-rice-legume crop sequences are described. Relative strengths and weaknesses of the model to simulate rice-rice-legume crop sequence are discussed along with the future directions for improvement.

Chapter 8 presents a general discussion of the results from all chapters with specific conclusions arising from this research and recommendations for future research in this area.

Full details of all references used within various chapters are given in the References section and any specific experimental data or other information not directly relevant to a chapter’s contents is given in the **Appendices** section.

CHAPTER II

Review of literature

2.1 Lowland rice-based cropping systems

Rice (*Oryza sativa* L.) is consumed by about 3 billion people and is the most common staple food of the largest number of people in the world (Maclean et al., 2002). Irrigated rice is mostly grown with supplementary irrigation in the wet season, and is entirely reliant on irrigation in the dry season. Lowland rice or irrigated rice usually refers to rice grown on the both flat and slopping bunded fields with surface flooded during most of growing season (George et al., 1992). Upland rice usually refers to rice grown on both flat and sloping fields without bunding where land is prepared under dry conditions with irrigation depending on rainfall (De Datta, 1975).

In many irrigated areas, rice is grown in a monoculture system with 2-3 crops per year depending on water availability. However, significant areas of rice are also grown in rotation with a range of other crops during non-rice season of year. The area under such rotation systems include rice–wheat (*Triticum aestivum* L.) rotation systems (Dawe et al., 2004; Timsina and Connor, 2001; Ladha et al., 2003) and rice-rice-oilseed and rice-maize (*Zea mays* L.) rotation systems (Bijay-Singh et al., 2008). Other crop rotation systems such as rice-rice-legume with occasional substitution of legume with another crop is a commonly practiced farming system by farmers in lowland of Indonesia, Bangladesh, Southern China, Myanmar, Philippines and Vietnam (Kueneman, 2006; George et al., 1992). Furthermore, legume crops are a potential source of nitrogen and carbon in soil that influence the soil's N supplying capacity for the succeeding crops, and may also enhance other aspects of soil fertility via improvement of other soil physical and chemical properties. Legume is usually planted as cash crop following rice as its residues improve the nitrogen and carbon status of the soil. Moore et al. (2000) reported that multi-cropping systems usually improve the organic carbon and nitrogen content of soil than monocropping systems. However, the extents and rates of legume residues and its effects on the succeeding crops remain unclear under the alternation of anaerobic during rice flooded and aerobic during legumes planted conditions in the tropical climatic.

Rice is usually transplanted into the puddled soil and farmers try to maintain a fixed depth of ponded water on soil surface throughout the cropping season. This practice of (lowland) rice production modifies soil structure considerably which may have negative implications for all the following cereal crops such as wheat, soybean and peanut (Hobbs and Gupta, 2003; Timsina and Connor, 2001). The cyclic transitions from anaerobic soil conditions during the rice crop to aerobic soil conditions during the succeeding legume crop and vice versa may have dramatic effects on the chemical and biological soil conditions affecting nutrient status and availability to these crops. Adverse effects of such crop sequences may cause yield stagnation or even decline which is a major concern for the sustainability of lowland rice cropping systems (Ladha et al., 2003). In addition, there can be additional impacts of crops rotation on land degradation and biological productivity (yield loses, carry over diseases of plant, reduce fertility of soil, etc.). Therefore, whole-farm models that include crop rotations are important components of research.

Most lowland rice-based cropping systems usually use fine texture soils with low percolation rates that allow an extended period of submergence. Soils become anaerobic under flooded that reduces nitrification allowing accumulation of NH_4–N which essential for growing lowland rice (De Datta, 1995). However, with increasing demand for rice and other crops to support growing population within major rice growing nations, coarse-textured soils are being used increasingly for both upland and lowland irrigated rice (Aulakh and Bijay-Singh, 1997; Aulakh and Pasricha, 1997).

Coarse-textured soils generally contain silt and clay in the range of 0.5 to 12 and 3 to 10%, respectively. These soils include sand, loamy sand and sandy loam in textural classes. These occur on a variety of land forms and relief such as dunes of various types, interdunes, sandy hummocky plains, sandy plains and recent alluvium along stream banks. Coarse-textures soils generally manifests in poor to weak structural development, low moisture and nutrient retention capacity, high infiltration rates and susceptibility to erosion. With high infiltration rates, coarse soils are usually characterised as a problematic group of soils for their land use, management and sustained productivity (Aulakh and Bijay-Singh, 1997).

In coarse-textured soils, flooding cannot be maintained over extended period due to high soil percolation rates. In these soils, the development of appropriate irrigation strategies to maintain yield with limited water supply is a high priority as globally rice production needs to increase by 70% by 2025 (Tuong and Bhuiyan, 1999) to meet projected demand.

2.2 Nitrogen dynamics in lowland rice-based farming systems

If water is not a limiting factor, crop growth and yield greatly depends on soil-N supply. Demand for nitrogenous fertiliser has been increasing in agriculture with the evolution of high-yielding crop varieties. Farmers generally apply as much fertilizer as resources permit to increase yield with little information on the amount of N required to sustain crop yield on different soils. Consequently, there is opportunity for residue of N to be left in the soil which may find its way into the atmosphere and surface and ground water sources through various chemical and physical processes, leading to environmental pollution. Enhanced above-ground biomass growth stimulated by excessive N availability in the soil can also cause higher transpiration rates, reducing available soil water during flowering and grain filling that may reduce grain yield as for winter wheat (Ritchie and Johnson, 1990; Nielsen and Halvorson, 1991). Hence, appropriate management of N fertiliser holds the key for a better environment and improved crop production.

The greatest source of available N is the atmospheric dinitrogen gas (N_2) which is relatively inert. Significant amounts of N enter the soil via rainfall or through the effects of lightning (Coyne and Frye, 2005). Dinitrogen (N_2) can be only used by specialized micro-organisms like bacteria, actionmycetes and cyanobactertia through symbiosis. Members of the bean family (legumes) and a few other plants form mutualistic, symbiotic relationships with nitrogen fixing bacteria. In exchange for nitrogen, the bacteria receive carbohydrates from the plants and form special structures (nodules) in roots as they can exist mostly in a moist environment (Stevenson and Cole, 1999).

Nitrogen is used by living organisms to produce a number of complex organic molecules like amino acids, proteins and nucleic acids. The store of nitrogen found in the atmosphere, where it exists as a gas (mainly N_2), plays an important role in all life processes. Other major stores of nitrogen include organic matter in soil and the oceans. However, nitrogen is often the most limiting nutrient and required in large quantities for plant growth. Plants can only take up nitrogen in two forms: ammonium ion (NH_4^+) and nitrate ion (NO_3^-). Most plants obtain the nitrogen they need as inorganic nitrate and ammonium from the soil solution (Stevenson and Cole, 1999).

Nitrogen is an important element in the soil and the biosphere (O'Hara et al., 2002), and has contributed much to the remarkable increase in food production that has occurred during the past 50 years in the form of nitrogenous fertilizers (Smil, 1999). In flooded rice, nitrogenous fertilizers are the most important sources of N nutrient. As rice production needs to be increased in future to cope with the food demand of a growing population, N fertilizer will need to be applied at nearly threefold the present rates (Cassman et al., 1998). However, N fertilizer efficiency in irrigated rice is low, with an apparent recovery of <40% (Cassman et al., 1993; 1996). The main reasons for low fertilizer efficiency are N losses by volatilization in the form of NH_3 gas and the processes of nitrification and denitrification. N loss by volatilization of NH_3 is influenced by algal photosynthesis in the floodwater that increases pH (Vlek and Byrnes, 1986).

The dynamics of nitrogen and carbon in rice-based cropping systems is affected by the alternation of anaerobic and aerobic soil conditions (Fierer and Schimel, 2002; Gu et al., 2009). Under flooded conditions, most N is available in ammonium (NH_4-N) form and taken up by rice and nitrification is restricted by a limited oxygen (George et al., 1992). When soil is dried, NH_4-N is transformed to NO_3-N via nitrification. As a result, nitrate accumulates in the soil during the aerobic condition. Upon flooding during rice growth period, excess mineral N that may not be taken up by the crops may be lost through leaching and denitrification (Reddy et al., 1989; Qiu and McComb, 1996). The extent of N loss mechanism depends on the amount of the nitrate in soil solution, the quantity of easily mineralisable carbon sources, the intensity of rain and the flow of water in the soil profile (Li, 2000; Pathak et al., 2002). The dynamics of soil mineral N under the alternation of anaerobic and aerobic soil conditions in lowland rice-based cropping systems is conceptualised in Fig. 2.1. These complex processes need to be clearly understood and quantified as a basis for improvement in yields as well as nitrogen and water use efficiencies in rice-based farming systems. Further details are given below on nitrogen transformation processes that include mineralisation, immobilisation, nitrification, denitrification and fixation.

2.2.1 Nitrogen mineralisation and immobilisation

Mineralisation refers to the decay or break down of organic-nitrogen fraction in soil and organic matter that can release mineral N (Socolow, 1999). Mineralisation also refers to ammonification because the reaction mainly releases mineral N in the form of ammonia, as in Eqn. 2.1 (Coyne and Frye, 2005). Organic fractions of N are usually present in the plant residues, fast and easily decomposable soil organic matter fractions and dead microbial material. Mineralisation of N from soil organic matter, dead animal or animal wastes and green manures, and crop residues (dead plant matter) contribute greatly to the soil N budget and to total N available to plants (Kolberg et al., 1996).

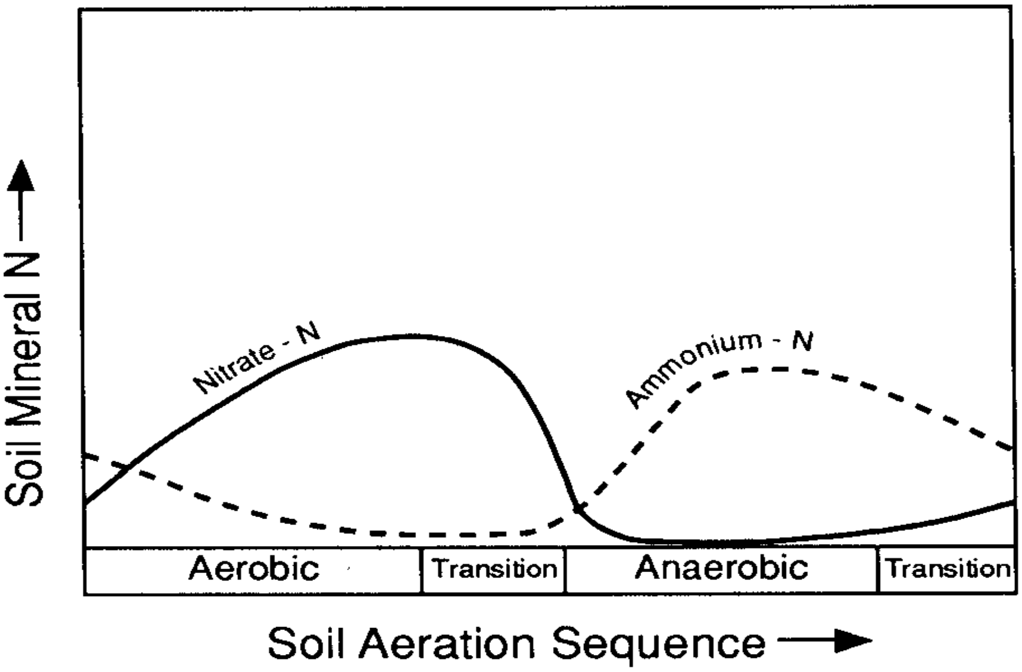

Figure 2.1 Schematic of soil mineral N dynamics under aerobic and anaerobic conditions in lowland rice-based cropping systems (George et al., 1992).

Various groups of soil microbes use the carbon in these organic matter fractions for development and growth as each group of microbes is specialised in feeding on a particular fraction of the soil organic matter (Paul and Clark, 1995). A flow of mineralised N mainly in the form of ammonium enters the inorganic nitrogen pools in the soil depending upon the C and N content of the decomposing organic material. The rates of N transformation processes can vary considerably as it is controlled by a diverse group of soil microorganisms that operate at different speeds depending on the type of organic sources present in the soil. For example, organic source of lignin is more resistant to microbial decomposition than other organic constituents in soil (van Veen and Paul, 1981; Parton et al., 1987).

$$\text{OrganicN(R-NH}_2\text{)} \rightarrow \text{NH}_3 \rightarrow \text{NH}_4^+ \quad (2.1)$$

Immobilisation or assimilation refers to a process opposite to mineralisation as inorganic N compounds in soil (mainly in the form of NH_4^+ and NO_3^-) are transformed into the organic form (such as N incorporated into plant and a microbial biomass) as given in Eqns. 2.2 and 2.3). This process renders N to become temporarily unavailable to the crop (Socolow, 1999; Coyne and Frye, 2005). Immobilisation primarily occurs during the growth of organisms which are involved in the decaying of organic matter. Microbes need carbon and nitrogen in order to grow. If the N requirement for microbial growth is not met, the microorganisms will immobilise the plant-available form of nitrogen i.e. ammonium and nitrate (van Veen et al., 1985; Tate, 1995). Immobilization can also sometimes refer to the binding of NH_4 ion to soil clays during to the interaction of inorganic N with soil organic matter (Coyne and Frye, 2005). Mineralisation and immobilisation processes occur widely in nature while fixation, nitrification and denitrification occur in some situations as it is accomplished only by special type of microorganisms.

$$\text{NH}_4^+ \rightarrow \text{OrganicN(R-NH}_2\text{)} \quad (2.2)$$

$$\text{NO}_3^- \text{ or NO}_2^- \rightarrow \text{NH}_4^+ \rightarrow \text{OrganicN(R-NH}_2\text{)} \quad (2.3)$$

2.2.2 Nitrification

Nitrification refers to the process of oxidation of ammonium form of N to nitrate form (Martens, 2001). This process occurs under aerobic conditions and is facilitated by species of nitrifying organisms (Prosser, 2005). The ammonium form of nitrogen (NH_4^+) can be adsorbed on the surfaces of clay and organic colloids and which can be released into soil solution from these colloids through cation exchange process. Upon release, most of the ammonium ions often chemically converted into nitrite ion (NO_2^-) by a specific type of autotrophic bacteria in soil (Delwiche, 1970; Coyne and Frye, 2005). Further modification of NO_2^- can occur rapidly in soil into nitrate (NO_3^-) by another type of bacteria (Eqn. 2.4). The conversion process is influenced by the availability of ammonium, oxygen, soil pH, temperature and soil water (Muller, 2000; Martin et al., 1998). Process-based crop growth models often use these parameters to elucidate the mechanisms of nitrification. Since NO_3^- is highly mobile and can be lost from the root zone of crops and contaminate the ground water in intensively fertilized cropping systems, management strategies can be used to reduce this type of N loss (Martens, 2001).

$$NH_4^+ \underset{+H^+}{\overset{-H^+}{\rightleftharpoons}} NH_3 \rightarrow NO_2^- \rightarrow NO_3^- \qquad (2.4)$$

2.2.3 Denitrification

Denitrification is the process by which oxidised forms of nitrogen (NO_3^- and NO_2^-) are transformed into reduced and gaseous molecular components (NO, N_2O and N_2) (Stevenson, 1982; Martens, 2001). Denitrification is commonly an anaerobic soil process, where micro-organisms use nitrate as oxygen donor when decomposing organic matter. Schematic pathway and enzymes involved in the denitrification process is presented in Fig. 2.1. This process is controlled by soil moisture and redox potential (Steven et al., 1998), temperature and pH (Heinen, 2006; Ashby et al., 1998) and availability of substrates (e.g. dissolved organic carbon, NO_3, NO_2, NO, and N_2O). Denitrification tends to reduce soil nitrate content, so that less nitrate is available for uptake by plant and leaching (Haynes, 1986). Denitrification is also a cause of environmental concerns, as it contributes to emission of greenhouse gas of nitrous oxide (N_2O) from crop fields. Simulation models can be very helpful in examining the effects of denitrification on the nitrogen balance in agricultural systems.

A number of different approaches have been used to develop denitrification sub-models within the N-cycling models (Parton et al., 1996) using a combination of microbial growth models, soil structural models and simplified process models. The microbial growth models consider the dynamics of microbial organisms responsible for the N cycling processes. This approach has been used for the RZWQM (Root Zone Water Quality Model) model (Ma et al., 2001), the ECOSYS (Ecosystems) model (Grant, 2001) and for the DNDC (Denitrification-Decomposition) model (Li et al., 1992; Li et al., 2000).

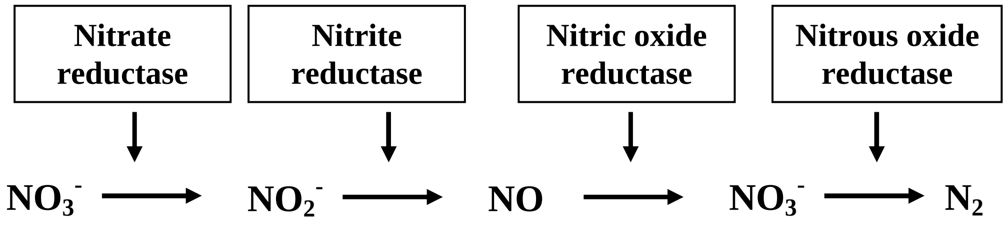

Figure 2.2 Schematic pathway and enzymes involved with denitrification of nitrogen (Martens, 2005).

The soil structural models consider diffusion of nitrogen various forms of gases into and out of soil aggregates. The distribution of aggregates in soil is also considered important as denitrification occurs only in the anoxic parts of aggregates (Arah and Smith, 1989; Grant, 2001; Vinten et al., 1996). The simplified process models consider the degree of saturation, soil temperature and nitrate content of the soil (Heinen, 2006). However, there are very few modelling attempts made to describe N-transformation in lowland rice-based cropping systems. Nitrogen transformation and distribution processes in ponded rice fields are different from other dryland crops (e.g. a legume crop) which may follow rice in the same field. For this reason, it is usually difficult to accurately assess the effects of nitrogen fertiliser application on N-transformation and productivity of an entire cropping system that includes rice and other crops.

2.2.4 Fixation

Fixation refers to biogeochemical conversion of N_2 gas in the atmosphere to the ammonia form arising from biological plant and microorganism association or lighting (Fisher and Newton, 2002). Giller (2001) proposed 5 groups of N_2-fixing organism. The first group includes class of bacteria known as rhizobia, the second group cyanobacteria (include a blue green algae), which are free-living species and form association with variety of plants. The third group includes actinomycetes, which form symbiotic association with flowering plants from a number of different families; the forth group is known as *Azospirillum* species, which are more loosely associated with plants and colonise the root epidermis of host species such as wheat, maize and rice plants (Vande-Broek et al., 1993); and the final group includes free-living N_2-fixers such as *Azotobacter* sp. that live in the soil. Biological fixation of atmospheric nitrogen gas (N_2) is critical in maintaining sustainable level of crop yields without requiring high level of external fertiliser-N inputs. The actual and potential contribution of biological N_2-fixation with N-nutrition in tropical cropping systems has been reviewed in detail by Giller (2001) and Postgate (1998). The remainder of this section will focus on rhizobia bacteria as the dominant group of N_2-fixing species that is known for its contribution to the productivity of tropical cropping systems.

Rhizobia are bacteria of several genera that induce and infect nodules on the roots and/or stems of plants of the family *Leguminosae* (Giller, 2001). These plants are also known to have the ability to form root nodules that host rhizobium. Decomposition of root nodules releases N into soil is helpful for plant nutrition. For this reason, legumes contribute to increased productivity of other crops when incorporated into a cropping system by directly increasing agricultural productivity and indirectly with restoration of soil fertility. The process of N_2-fixation is the reduction of N_2 gas in the atmosphere (including soil atmospheric) to a biologically useful form of ammonia-N. Because N_2 is highly stable, it needs high energy to break the molecules during conversion to ammonia and involves the enzymes of nitrogenase as follows (Giller, 2001):

$$N_2 + 8H^+ + 8e^- + 16ATP \rightarrow 2NH_3 + H_2 + 16ADP + 16Pi \qquad (2.5)$$

Nitrogen-fixing crops and pastures are essential components of many agricultural systems in sustaining productivity (Graham and Vance, 2000). As mentioned above, a clear benefit from use of these symbiotic legumes in many agricultural systems is primarily due to the fixation of atmospheric nitrogen by the root-nodule bacteria located in the root nodules of legume (Fisher and Newton, 2002). The productivity and nitrogen fixation by legumes in farming systems are affected by several abiotic factors including temperature, water, nutrients availability and pH (O'Hara et al., 2002).

Excess availability of nitrate in soil can affect nodule formation in many rice-based farming systems as shown with application of nitrogenous fertiliser to the legumes (Chen et al. 1992; Starling et al. 1998; Daimon et al. 1999; Taylor et al. 2005; Ray et al. 2006; Basu et al. 2008; Selamat and Gardner 1985; Daimon and Yoshioka, 2001).

2.3 Water management practices in lowland rice farming systems

On a global scale, irrigated agriculture uses about 70% of the available fresh water resources (FAO, 2007). With rapid increase of the world population and the corresponding increase in demand for extra water by other sectors such as industries and municipalities has forced the agricultural sector to use irrigation water more efficiently by using less water to produce more food. Defining strategies in planning and management of available water resources in the agricultural sector has become a national and global priority (Smith, 2000). Rice is one of the biggest users of the world's freshwater resources because it is mostly grown under flooded or submerged condition (Tuong and Bouman, 2003; Bouman and Tuong, 2001; Tuong et al., 2005). However, water is becoming increasingly scarce raising concerns over the sustainability of irrigated agriculture (Rijsberman, 2006). Bouman et al., (2007) predicted that by 2025, 15-20 million hectares of irrigated rice will experience some degree of water scarcity. Many rainfed areas are already drought-prone under present climatic conditions and are likely to experience more intense and more frequent drought events in the future due to climate change (Wassmann et al., 2009). Increasing water productivity is especially important because many processes in rice production area are related to water (Bouman, 2007). Therefore, efforts to reduce water use are of great significance in the rice-based cropping systems.

Most irrigated rice in the tropical Asian countries are raised in a seedbed and then transplanted into a main field (De Datta, 1981). Preparation of the main field consists of soaking, plowing and puddling (i.e. harrowing under shallow submerged conditions). Puddling is not only done for weed control, but also to increase water retention and reduce soil permeability, making it convenient to level the top field and transplanting (De Datta, 1981). After land preparation, the main growth period of rice starts from transplanting to harvest. At the field level, large reduction in water input can potentially be realised by reducing the seepage and percolation flows and by minimising land preparation time. Seepage and percolation losses can be reduced by effective water management. The opportunities and constraints of various water management approaches in lowland rice includes saturated soil culture (Borell et al., 1997; Tabbal et al., 2002), submerged and non-submerged water regime also known as alternate wetting and drying (Li, 2001; Tabbal et al., 2002) and aerobic rice (Bouman et al., 2002). These water management practices are briefly discussed in the next sections including continuously submerged water regime.

2.3.1 Continuously submerged soil

The rice crop grows better under continuously submerged soil conditions than other crops because its root can tolerate the anaerobic soil condition. This water regime keeps the rice field continuously flooded with water ponded depth of 5–10 cm from transplanting to harvesting. Continuously submerged irrigation practice changes the quality of soil organic matter (Olk and Senesi, 2000), but it is remarkable sustainable in maintaining adequate nutrient-supplying capacity and soil carbon (soil organic matter) and yield (Dawe et al., 2000). However, the cultivation of rice under continuously submerged irrigation practices requires approximately1000 - 3000 m^3 of water to produce 1000 kg of rice grain which is up to 3 times higher than the water required to produce a similar quantity of wheat (Wassmann et al., 2009).

2.3.2 Alternately submerged and non-submerged (ASNS)

Alternately submerged and non-submerged (ASNS) irrigation practice or alternately wetting and drying (AWD) is the technique of irrigation which requires water to sufficiently maintain 2-5 cm of floodwater depth over the field 2-7 days after the disappearance of floodwater. Changes from saturation to partially aerobic soil conditions in ASNS affect the form, availability and losses of nutrients such as nitrogen from the crop field. Tabbal et al. (1992) reported the level of ammonium in the soil to be lower and nitrate higher under ASNS than under fully flooded rice fields. Upon subsequent flooding, nitrate could be leached or undergo denitrification losses making overall N losses under ASNS higher than under conventional flooding. However, Belder et al. (2004) reported N uptake and fertilizer-N recoveries to be similar under flooded and AWD conditions in experiments, where the shallow groundwater table kept the soil relatively wet during the non-submergence period. Further research is needed to determine the level of "dryness" under ASNS that does not reduce N-use efficiency. In coarse-textured, alkaline soils with a high pH, the other problems may arise due to deficiency of certain availability of micronutrients under conditions of non-saturated soil as such under raised beds, aerobic rice and ASNS water regime as suggested by Bouman et al. (2005). Sharma et al. (2002) and Singh et al. (2002) have also reported iron and zinc deficiencies in raised beds and in direct-seeded rice systems under the ASNS irrigation regime.

The performance of ASNS in terms of rice yield, water input and water productivity depends much on the other environmental conditions such as soil type, water table depth and the number of days of absence of floodwater. When the water table coincides with root zone, the drying period may not sufficiently expose the rice plant to water stress to give comparable rice yield as with continuously submerged conditions. Belder et al. (2004) reported that biomass and yield of rice was not significantly different between ASNS and continuously submerged water regimes, but water productivity was significantly higher under ASNS than under continuously submerged in two out of three experiments on silty clay loam soils with shallow groundwater table and a percolation rate of 1-4.5 mm day^{-1}. However, when the water table was below the rooting zone, rice yield under ASNS was lower than under continuously submerged water regimes. Cabangon et al. (2003) reported that rice yield declined significantly under ASNS when the soil water potentials at 10 cm depth dropped below -20 kPa. Similar results have been also reported by Hira et al. (2002).

2.3.3 Saturated soil culture

The main water management in saturated soil culture is that the soil is kept as close to saturation as possible by shallow irrigation so that about 1-cm floodwater depth is obtained everyday after disappearance of standing water (Tuong et al., 2005). Tabbal et al. (2002) reported that saturated soil culture reduced water input by 30-60% compared with the conventional practice in Central Luzon, Philippines, while reduction of yield was only 4-9%. However, implementation of saturated soil culture requires assured water supply throughout the growth period at the field level and frequent shallow irrigation is labour intensive. In coarse-textured soils with a deep water table, the saturated soil culture can be difficult to accomplish because of higher percolation rates compared with fine-textured soil.

2.3.4 Aerobic rice

Bouman (2001) has introduced the term of ‘aerobic rice’ to describe a system of growing high-yielding rice varieties in non-puddled soil without standing water similar to irrigated upland crops such as maize or wheat. Peng et al. (2006) reported that yield difference between aerobic and flooded rice ranged from 8 to 69% depending on the number of seasons that aerobic rice is grown continuously, the length of dry and wet seasons, and the suitability of variety. Total water use of aerobic rice was 27–51% lower and water productivity 32–88% higher than that of continuously submerged water regime in fine-textures soil in Philippines. After six continuous seasons of aerobic rice cropping, there was a gradual decline in yield for variety Apo (compared with flooded conditions), although such a trend was not obvious when all tested varieties of rice were considered together (Bouman et al., 2005). However, the large yield gap (8 - 69%) between aerobic and flooded rice and reduction in yield of continuous aerobic rice could outweigh the benefit of water saving irrigation practices.

The reasons for yield decline in aerobic rice system need further investigation. Recent reports by Kato et al. (2009) indicate that the average yield under aerobic conditions can be similar or even higher than that with the flooded condition with yield of 7.9 t ha^{-1} in 2007 and 9.4 t ha^{-1} in 2008 for aerobic versus 8.2 t ha^{-1} for flooded water regimes. In this study, the average water productivity under aerobic conditions was 0.8–1.0 kg grain m^{-3} water using a super-high-yielding rice cultivar. In general, cultivation of high-yielding rice varieties in aerobic soil is a promising technology that maintains high productivity and conserves water. With a continued breeding program, future aerobic rice varieties will possess increased number of spikelets and sufficient adaptation to aerobic conditions such that yields comparable to the potential yield under flooded rice can be achieved consistently (Kato et al., 2009).

2.4 Water balance

Lowland rice is traditionally grown under continuously flooded condition that requires maintenance of about 5–10 cm of standing water throughout the growing period. This practice not only meets the water needs of rice, but provides an efficient supply of nutrients and is an effective method for weed control;. This and related practices of soil puddling to reduces percolation rates and construction of bunds (embankments) along the field boundary to prevent runoff complicates the computation of soil water balance. The estimation of soil water balance requires information on rainfall, irrigation amount, evapotranspiration, infiltration and runoff (Ritchie, 1998) as shown in Fig. 2.3.In general, the water balance of a puddled rice field is given by:

$$W = R + IR - ET - DP - Q \qquad (2.6)$$

where W is the depth of water stored within root zone; R is the rainfall over the surface; ET is the crop evapotranspiration including any evaporation of free water from the standing pool of water; DP the deep percolation beyond the root zone; IR is the amount of irrigation and Q the surface runoff. These components are usually expressed in units of (mm) depth and can be computed on daily basis. Contribution of capillary rise from the groundwater is usually ignored as the puddled soil layer remains saturated for a considerable period during the crop growth and has a higher soil moisture potential than at the capillary fringe located below the puddled soil layer (Odhiambo and Murthy, 1996).

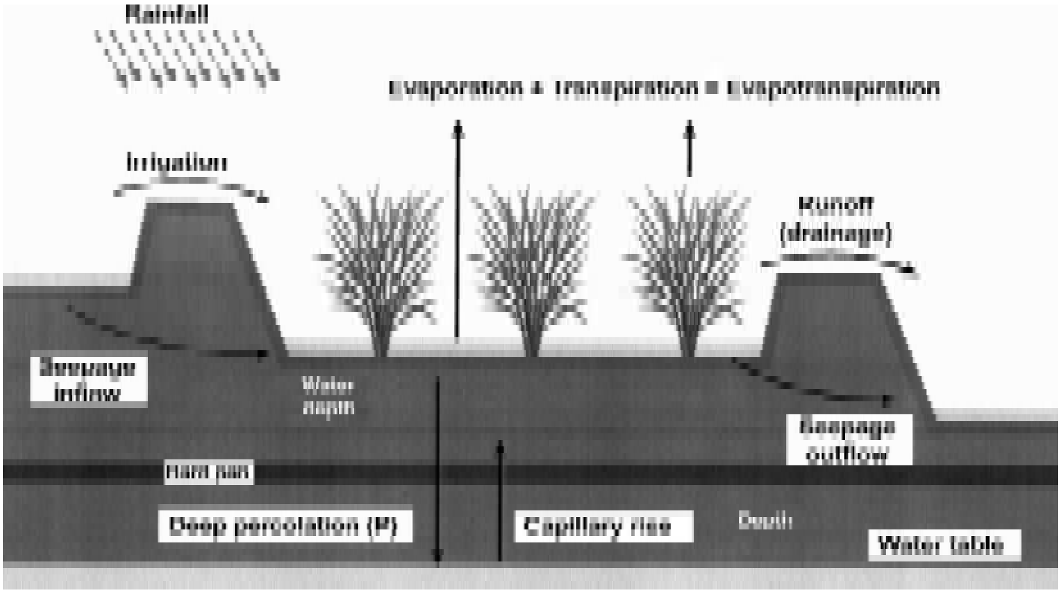

Figure 2.3 Components of water balance in flooded rice field (Tabbal, 2002)

2.4.1 Surface runoff (*Q*)

Runoff is generated from a field when infiltration rate exceeds the rainfall rate at the soil surface. Surface ponding occurs first when rainfall occurs over a saturated soil surface (McFarlane et al., 1993). In lowland rice cropping systems, rainfall in excess of bund height leaves the system as surface runoff:

$$Q = R - BH \tag{2.7}$$

where BH is the bund height (mm) and R the accumulated rainfall over the surface (mm). This surface runoff can be an input of overland flow to a neighbouring field. However, when this is involved in a sequence of fields, neighbouring fields will also pass on the surface runoff from adjusting fields until the runoff reaches a drain.

2.4.2 Deep percolation (P)

Percolation is one of the negative components of water balance as it is the vertical downward loss of water beyond the crop's root zone. Percolated water is unavailable to the crop. The rate of percolation is governed by the hydraulic conductivity of the soil within the root zone and the depth of standing water in the field. Variation in percolation rate is usually influenced by the water regime within and around the field. An increased in the depth of ponded water increases percolation due to an increase in the hydraulic gradient (Sanchez, 1973). Because of puddling, the soil layer at the bottom of the root zone, i.e. approximately 20-30 cm below the soil surface, gets compacted that reduces the saturated hydraulic conductivity compared to the unpuddled fields. Darcy's law is commonly used for the estimation of daily percolation rate below the root zone (Odhiambo and Murthy, 1996; Singh et al., 2001) and this given as:

$$DP = K_s \frac{\Delta H}{\Delta Z} \tag{2.8}$$

where DP is deep percolation beyond the root zone (mm per day); k_s is the saturated hydraulic conductivity (mm per day; after accounting for puddling effects) and $\Delta H/\Delta Z$ is the hydraulic gradient.

2.4.3 Evapotranspiration (ET)

Evaporation from the water covered soil surface and transpiration from the plant leaves are combined and treated together as evapotranspiration (ET). ET for a rice crop is strongly dependent on climatic conditions. Maintaining ET at the potential rate, i.e. the rate at which it is not hindered by water shortage, is essential for obtaining high yield of rice (IRRI, 1987) because rice yield usually declines with decreasing rate of ET. Crop coefficients are often used in the estimation of actual evapotranspiration from reference ET for specific regions as recommended by FAO (Doorenbos and Pruitt, 1977). The following relationship will be used to estimate daily mean evapotranspiration (Doorenbos and Pruitt, 1977):

$$ET = K_c \times ET_0 \tag{2.9}$$

where ET_0 is the reference crop evapotranspiration (mm); K_c the crop coefficient and ET the crop evapotranspiration.

2.5 Modelling rice-based cropping systems

Crop growth simulation models are recognized as valuable tools in agricultural research. It can help to compare experimental research findings across sites, extrapolate experimental field data to wider environments, develop management recommendations and decision-support systems, explore the effects of climate change, and make yield predictions (Bouman et al., 1996; Jones et al., 2003).

Cropping system models integrate data by using the knowledge of soil, plant, and atmosphere systems to allow simulation of cropping systems over a wide range of environments and management practices (Larson et al., 1996; Pala et al., 1996; Cavero et al., 1998; Alves and Nortcliff, 2000; Mailhol et al., 2001). Such simulation models have been developed for a number of annual crops including wheat, rice and potatoes (van Laar et al., 1997; Bouman et al., 2001; Wolf, 2002). This makes them valuable tools for agricultural professionals around the world as these can provide an insight of the functioning of cropping systems by applying a system approach (Leffelaar, 1999). However, effective application of cropping system models requires a minimum set of weather, soil, and management data (Hunt and Boote, 1998) together with additional data such as time-series data on crop development, yield and yield components, soil moisture, and soil nutrients.

2.5.1 Rice model

Modelling of growth, development and production of rice began more than 30 years ago. The development of rice model has been reviewed in detail by Bouman and van Laar (2006). In brief, the International Rice Research Institute (IRRI) published the model RICEMOD (rice model) for potential production of rice in rainfed environments in 1983 (McMennamy and O’Toole 1983). Due to its simplicity, the model did not receive widespread recognition. Further progress with rice model was developed by Horie et al. (1992; 1995) which allowed development of Simulation Model for Rice-Weather Relationships (SIMRIW) to predict production potential of rice in Japan and to predict the effects of climate change.

CERES-Rice is a generic and dynamic simulation model which is a part of the DSSAT (Decision Support System for Agricultural Technology) suite of models (Godwin and Jones 1991; Godwin and Singh 1998; Ritchie et al., 1998; Jones et al., 2003). This model includes a detailed description of crop growth under optimal, nitrogen-limited and water-limited conditions. It is relatively widely used although the model has been only partially described in different publications (Timsina and Humphreys, 2003; 2006). From all the cases that Timsina and Humphreys (2003) investigated, CERES-rice was found to be calibrated and evaluated only once using experimental data for more than one site or for more than one season. Model evaluations were generally limited to graphical comparison of simulated and measured crop growth output with little indication of quantitative goodness-of-fit parameters.

In the mid 1990s, IRRI in collaboration with Wageningen University and Research Centre developed the ORYZA model series to simulate growth and development of tropical lowland rice (Ten Berge and Kropff, 1995). The first model was ORYZA1 for potential production of rice (Kropff et al., 1994), that was soon followed by ORYZA_W for water-limited production (Wopereis et al., 1994), and ORYZA-N (Drenth et al., 1994) and ORYZA1N (Aggarwal et al., 1997) for nitrogen-limited production of rice. A new version in the ORYZA model was released in 2001 that improved and integrated all previous versions into one model called ORYZA2000 (Bouman et al., 2001). ORYZA2000 simulates growth and development of lowland rice without any limitation to potential production, and with water and nitrogen limitation. However, the ORYZA2000 model can be used for single crop and single season of rice. The model cannot simulate growth of multiple crops within a cropping system and cannot simulate residual effect of nitrogen and soil water remaining in soil for the subsequent crops as expected within a cropping system. In ORYZA2000, N availability in soil is modelled as a simple book-keeping routine and does not compute how N transformation processes vary in the soil over time (Bouman and van Laar, 2006).

2.5.2 APSIM-Oryza model

With the increased focus on sustainable landscapes in which farms are an important part of the landscape, there is an increased focus on building models of farming systems to assess the agricultural, economical and environmental impacts of farming at various scales. These whole-farm models are able to predict the impacts of different scenarios such as different farm management options and the effects of changes in policies, markets, resources or other regulations. Furthermore, there is an increasing demand to simulate the sustainability of rice-based cropping systems, especially in Asia. Such a modelling capability will allow investigation of nitrogen dynamics, crop sequence, intercropping, crop residue management and soil and water management in rice-based cropping systems (Keating et al., 2003; Wang et al., 2003).

A cropping system model, APSIM (Agricultural Production System Simulator), developed in Australia is able to predict crop growth, yield, nitrogen uptake, nitrogen dynamics in soil and rotation effects on crop residue over a long period (Keating et al., 2003). System-related processes are available to any crop module from APSIM's infrastructure and generic crop library (Wang et al., 2003). However, APSIM is based on dryland farming systems rather than lowland paddy farming systems and have been rarely used for cropping system of the tropical regions. Furthermore, APSIM has not been developed simulate growth of upland or lowland paddy (Keating et al., 2003). Lowland rice has a relatively more complex carbon and nitrogen dynamics compared to other crops because it includes transformation and leaching of nitrogen between a water-ponded region and oxidized and reduced soil layers. The alternation between anaerobic condition during ponded rice growth period and aerobic condition during the dry season of a succeeding legume crop in a rice-rice-legume rotation provides a modelling challenge to simulate these characteristics of lowland rice-based cropping systems. Currently the model is lacking the capability to simulate these processes (Keating et al., 2003; Zhang et al., 2007). Various relevant chemical and biological processes that occur in a long-term ponded field have been unavailable within APSIM modules.

Gaydon et al. (2009) has recently developed a new functionality, 'Pond module', that can be incorporated into the framework of APSIM (Keating et al., 2003). APSIM-Pond describes the biological and chemical processes responsible for the loss/gain of C and N in rice ponds including algal turnover and biomass incorporated in rice-based farming systems (Gaydon et al., 2009). APSIM now has a capability to simulate growth and development of rice and it includes other important features of a rice cropping system such as fertilisation, transplanting and field management practices for the alternation of aerobic and anaerobic environments in rice-based cropping systems. It also includes important aspects of rice physiology, such as photosynthesis, phenological development and yield as simulated in ORYZA2000 using the existing APSIM modules for water, nitrogen and other soil properties and management aspects. Such a system capability will allow investigation of rice-based cropping systems and carry-over effects for improved decision-making in the management of a wide range of crops. The versatility of the model can be increased to simulate the nitrogen dynamics of lowland paddy and productivity of rice-rice-legume rotation systems typically practiced in Asian countries.

2.6 Summary

Increased rice production is needed to meet the future population growth with limited area of arable land and restricted water supply. Coarse-textured soils are now used in tropical regions for raising both upland crops and lowland irrigated rice. However, it is difficult to maintain continuous flooding conditions in porous soils under rice due to high losses of water via percolation. Since rice is one of the biggest users of fresh water, it is clear from this literature review that research on water management is needed to conserve water and increase water use efficiency by producing more rice with less water in an irrigated production system. Crop growth and yield greatly depend on supply and availability of soil N. However, efficient utilisation of the applied N via fertilisers remains very low, that is around 20-40%. If nitrogen application and irrigation are not appropriately managed, significant amount of nitrogen could be lost. The fate of applied N should be studied quantitatively to determine the extent of negative impacts on the environment. Nitrogen transformation and distribution in rice-based cropping systems are too complex to accurately assess the effects of applied nitrogen fertiliser on the productivity of the succeeding crop within the cropping system. Crop simulation models of APSIM-Oryza can help synthesize this and other information and may provide a way of extrapolating this information to other regions of interest. However, models of rice-based cropping systems of APSIM-Oryza are yet to be calibrated and validated to increase our confidence in simulating rice-based cropping systems over a sufficient period.

CHAPTER III

Methodology of Field Experiment

This chapter provides details of the materials and methods used in this study including details of experimental site and design, soil type, climate data and sampling method for lowland rice-based cropping systems involving rice and legume crops.

3.1 Site and climate

A field experiment with lowland rice (*Oryza sativa* L. cv Cigeulis) and legumes (details given later in this chapter) was conducted at the Experimental Station of the Assessment Institute for Agricultural Technology (BPTP) in the Lombok island, West Nusa Tenggara Province (NTB) of Indonesia (08°35′N, 116°13′E, 150 m elevation) to evaluate water and nitrogen management strategies in the tropical lowland rice-based cropping systems (Fig. 3.1). Rice–rice-legumes are the typical crop sequences practiced in this region.

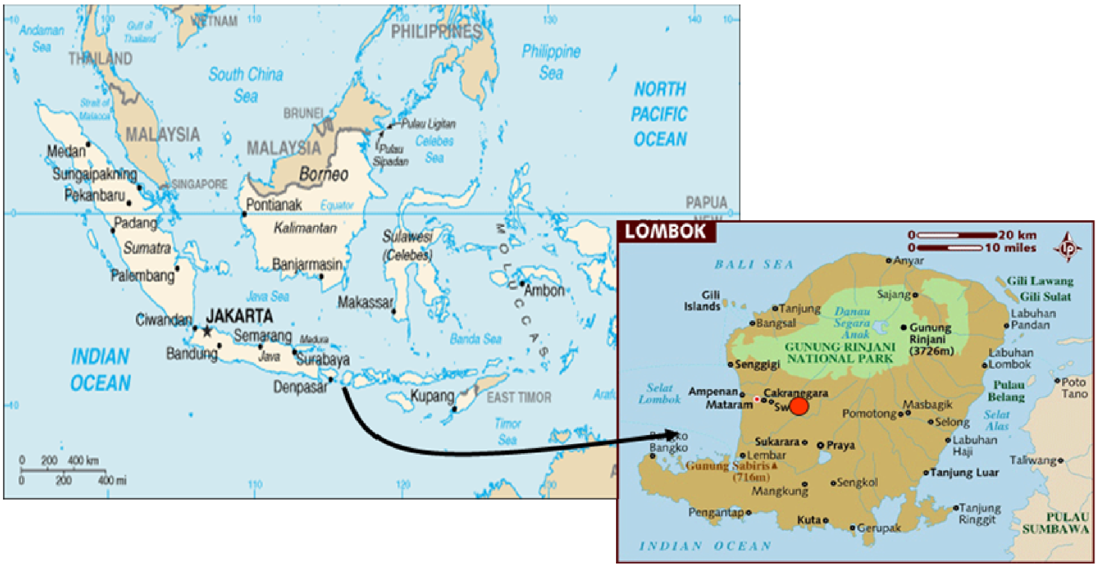

Figure 3.1 Map of Indonesia and Lombok Island where the experimental site was located (dot red). (Source:http://www.mapsofworld.com/indonesia/maps/indonesia-political-map.jpg).

Daily weather data consisting of maximum and minimum temperature, radiation and rainfall were collected from a weather station at the experimental site. The climate of this region is tropical and humid and is strongly influenced by the monsoon with a long-term annual average rainfall of 2376 mm. Approximately 70–80% of the total rainfall is distributed during November-April (Fig. 3.2). The mean daily minimum air temperature ranged from 20.12°C in August to 24.0°C in December, while maximum temperature ranged from 29.98°C in July to 31.76°C in November. The low and high mean radiation ranged from 16.48 - 20.7 MJ m^{-2} day^{-1} in November to March and from 22.04 - 25.03 MJ m^{-2} day^{-1} in April to October, respectively (Fig. 3.3).

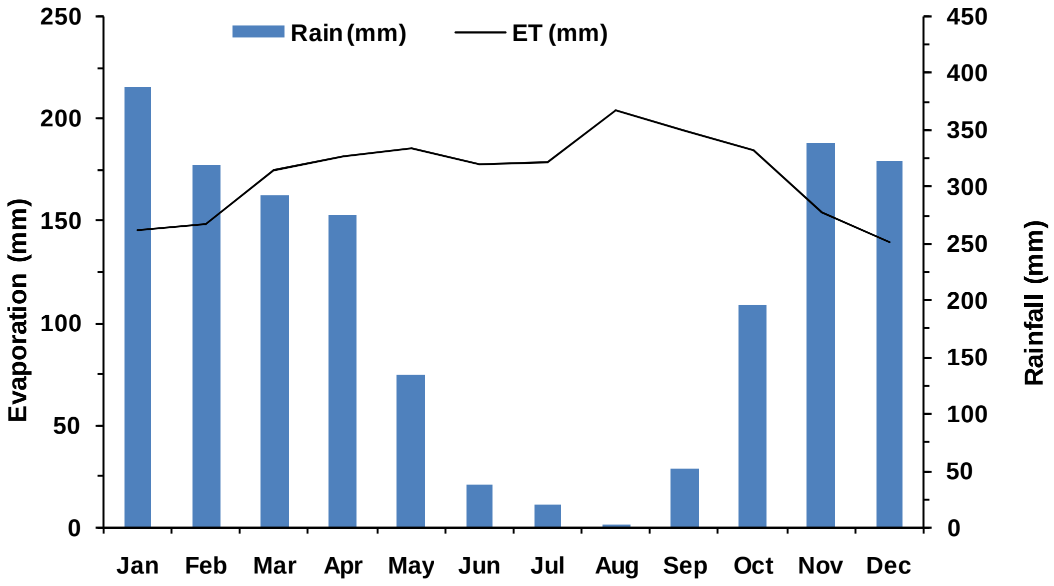

Figure 3.2 Average monthly rainfall and evaporation (ET) over 13 years (1997-2009) at the experimental site.

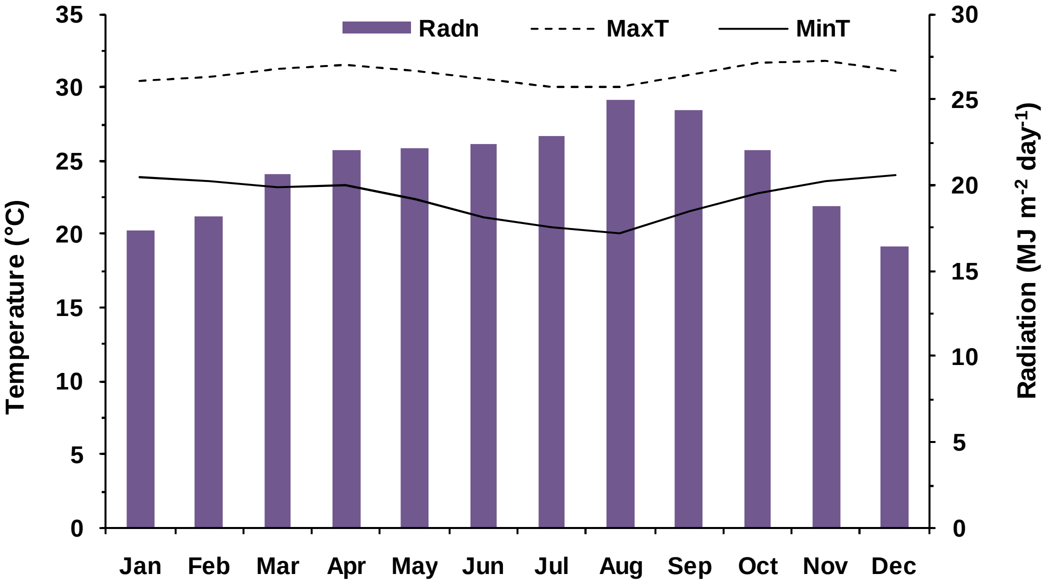

Figure 3.3 Average daily radiation (Radn), maximum (maxT) and minimum (minT) temperature over 13 years (1997-2009) at the experimental site.

The soil at the experimental site is classified as a Typic Ustochrept (Soil Survey Staff, 2006). Selected physical and chemical properties of the soil at the experimental site are presented in Table 3.1. Soil texture was determined by sedimentation methods described by Gee and Bauder (1986). Soil texture within the top 100 cm at the experimental site varied with depth from sandy loam (within the upper 40 cm depth) to sand (at 70-100 cm depth). The sand and clay percentage of the soil varied within 56-90% and 4-14%, respectively with sand fraction increasing with soil depth while silt and clay fractions decreasing with depth. Soil bulk density also varied with depth in the range of 1.19-1.35 Mg m^{-3}. The highest bulk density was found at 20-40 cm, indicating that compacted zone (hardpan) was established at the experimental site Soil organic carbon was determined following Walkley and Black method as described by Allison (1965) Organic carbon content in the upper 20 cm soil was 1.61% and declined sharply to very low level (0.07%) at 70-100 m depth. This indicated that most of the organic carbon accumulated near the soil surface (0-20 cm). Soil pH (1:5 soil-water suspensions) remained close to neutral (7.0-7.4). Cation exchange capacity (CEC) was determined using methods described by Rayment and Higginson (1992). The CEC was within a range of 6.71 - 17.31 $cmol_c$ kg^{-1} and was highest at soil surface (0-20 cm depth) and decreased with soil. The level of mineral nitrogen in the soil varied with depth ranging from 0.06 – 0.12%, 3.98 – 12.28 mg kg^{-1} and 3.77 – 6.76 mg kg^{-1} for total-N, NO_3-N and NH_4-N, respectively.

Table 3.1 Properties of soil at various depths at the experimental site.

Soil depth (cm)	pH (1:5)	Total-N (%)	NO_3^--N	NH_4^+-N	P_2O_5	OC (%)	CEC cmol$_c$ kg^{-1}
			------------mg kg^{-1}--------------				
0-20	7.24	0.12	12.281	6.759	90.77	1.61	17.31
20-40	7.36	0.11	6.721	4.547	71.93	0.80	14.18
40-70	6.97	0.08	5.071	4.270	40.59	0.09	8.12
70-100	7.19	0.06	3.981	3.770	21.38	0.07	6.71
Soil depth (cm)	Soil fraction (%)			DUL (%)	BD g cm^{-3}	Porosity (%)	
	Sand	Silt	Clay				
0-20	56	32	12	29.6	1.19	55.1	
20-40	73	13	14	27.2	1.35	49.2	
40-70	85	9	6	23.1	1.27	51.9	
70-100	90	6	4	20.9	1.23	53.4	

Notes: pH measured at 1:5 soil: water suspensions; OC = organic carbon; CEC = Cation Exchange Capacity; DUL = Drain Upper Limit (field capacity); BD = bulk density. Phosphate was analysed using Bray's method. Porosity was calculated from Soil Bulk Density using; Porosity (%) = 1-(BD/2.65)*100.

3.2 Rice experiment

3.2.1 Experimental design

The field experiments were conducted during October 2007 to November 2009 over 6 cropping seasons to grow two crops of wet rice, dry rice and legumes. The cropping calendar for various seasons of rice in wet and dry seasons including growth stages for the field experiment, crop management and sampling activities is shown in Table 3.2. The experiment was based on a split-plot design consisting of three replicates of all treatments within a given block. Two irrigation treatments (referred to as CS and ASNS to indicate continuously submerged and alternately submerged and non-submerged treatments, respectively) were randomly allocated as main plots and three rates of N-fertilization (referred to as F0, F1 and F2 treatments to indicate the application of 0, 70 and 140 kg N ha^{-1}, respectively) as subplots within each main plot (Figure 3.4).

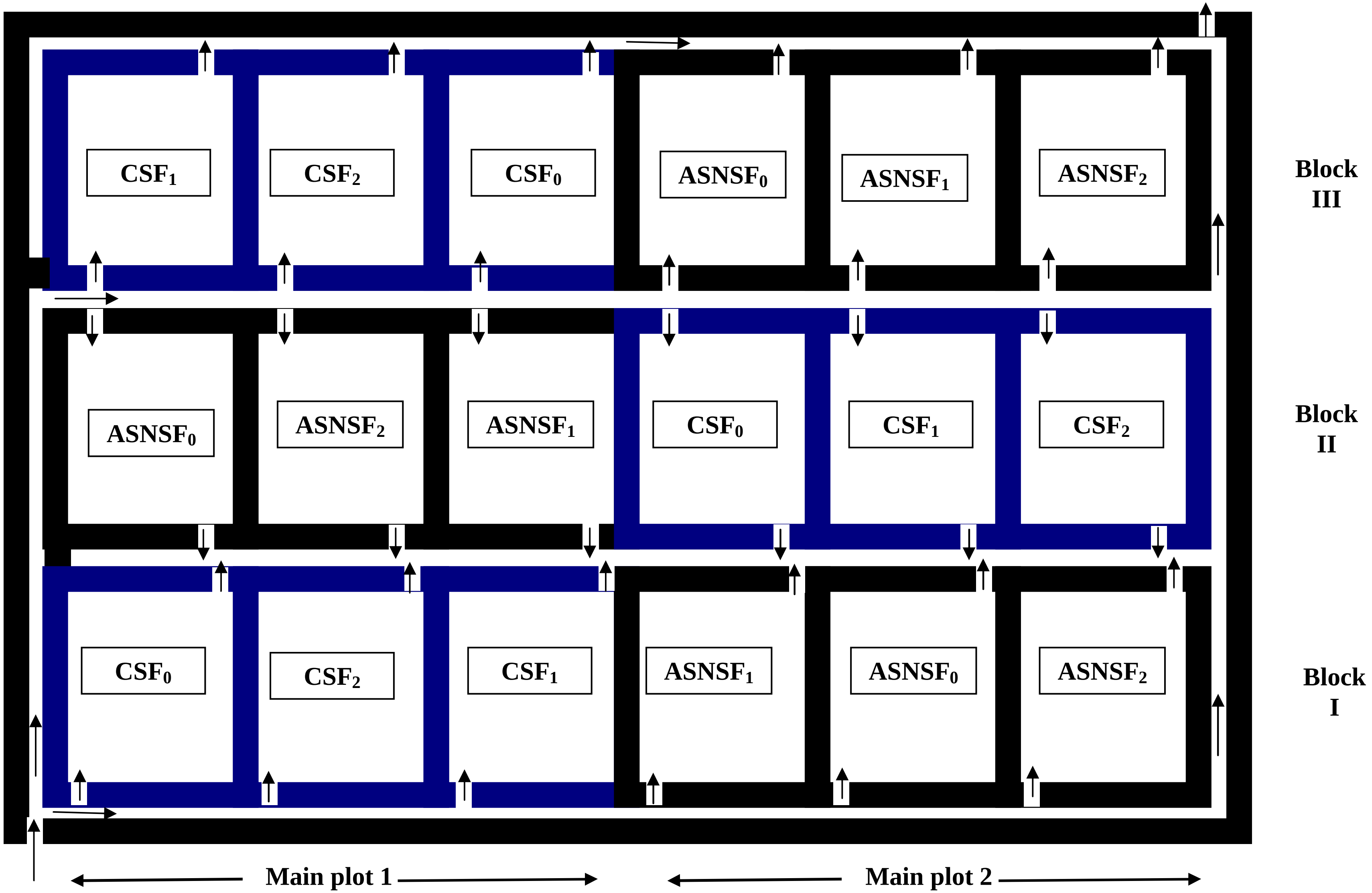

Figure 3.4 Layout of the field experiment. CS = continuously submerged; ASNS = alternately submerged and non-submerged; F_0, F_1 and F_2 = 0, 70 and 140 kg N ha^{-1} respectively. Arrows indicate inflow and out flow water

Plot size was 5 x 6 m^2 and black polyethylene plastic sheets were inserted to a depth of 0.8 m from surface in the middle of the bund (mounds to separate adjoining plots) to minimise seepage of water and loss of fertiliser from plots. Bund size was 0.4 m height by 0.4 m width and distance between a block was 0.4 m for inflow and outflow irrigation.

3.2.2 Field preparation

Preparation of the rice plots started about one month before the rice was transplanted. The plots were first flooded for a few days and ploughed twice by hand with a hoe across the plots to disturb the soil within a depth of 15-20 cm. The soil was then puddled 3-5 days after ploughing and finally levelled using a levelling board. A space of 20 × 20 cm was marked and used at the time of transplanting rice seedlings.

3.2.3 Rice planting

Rice seeds of the high yielding inbred variety ‘Cigeulis’ were first pre-germinated by soaking in water for 24 hours and placed under shade by covering the seeds with hessian (gunny) bags for 2 days. Pre-germinated seeds were then broadcast in nursery beds and covered with some decomposed manure. Once the seedlings were established, the nursery was irrigated to raise the water level gradually to accommodate the growing plant. This method of raising seedlings is referred to as wet-bed method (Basra et al. 2007). After 17 days, seedlings were removed by hand from the nursery and transplanted into experimental plots by hand at a spacing of 0.2 × 0.2 m with 1 seedling per hill.

3.2.4 Fertiliser application

Urea was used as nitrogen fertiliser and was split into 3 applications viz. 20% at 7 days after transplanting (DAT), 30% at 29-34 DAT, and 50% at panicle initiation (45-50 DAT). Nitrogen fertiliser rates were 0, 70 and 140 kg N ha^{-1} hereafter referred to as F0, F1 and F2, respectively. The 140 kg N ha^{-1} was locally recommended N fertiliser application rates in the area of study. However, farmers usually apply 184-230 kg N ha^{-1} which is higher than the recommended rate (Wirajaswadi et al., 2002). Phosphorus and potassium fertilizers were applied to all plots at the rates of 100 kg TSP (triple superphosphate) ha^{-1} and 50 kg KCl (potassium chloride) ha^{-1}, respectively as basal fertiliser before transplanting of rice.

3.2.5 Irrigation

Each main plot was irrigated separately and the amount of water measured using V-notch weirs installed at the entry point of each main plot. Simplified discharge rate of V-notch weirs can be expressed as follows (US Bureau of Reclamation, 2001):

$$Q = 4.28 \times C \times \tan(\theta/2) \times (h + k)^{5/2} \tag{3.1}$$

where Q = flow rate $\text{ft}^3\ \text{s}^{-1}$, C = effective discharge coefficient; h = head on the weir in ft; k = head correction factor at any notch angle. The head correction factor (k) and discharge coefficient (C) are both functions of notch angle (θ) as shown in Fig. 3.5. A schematic diagram of V-notch weir is shown in Fig. 3.6. Measurement of h over the duration of irrigation time (s) allowed calculating the volume of water applied during an irrigation event. Water depth of irrigation was calculated by dividing the volume of water applied by main plot area.

A pump with discharge rates of 33 $\text{m}^3\ \text{h}^{-1}$ was also installed to pump water in a storage pond close to the experimental site to irrigate the plots when water was not available at irrigation channel. The date and amount of irrigation applied were recorded.

Table 3.2 Cropping calendar for four rice growing seasons during 2007 – 2009 at the field experiment.

Crop management and sampling activities	Rice seasons				Comments
	2007-2008 (wet season)	2008 (dry season)	2008-2009 (wet season)	2009 (dry season)	
Nursery sowing	06 Nov 07	14 Mar 08	15 Nov 08	13 Mar 09	
Basal fertiliser	20 Nov 07	30 Mar 08	1 Dec 08	29 Mar 09	100 kg TSP ha^{-1} (triple super phosphate) and 50 kg KCl ha^{-1}
Transplanting	23 Nov 07	02 Apr 08	02-Dec 08	01 Apr 09	Plant spacing: 20 × 20 cm
1st urea fertiliser applied	30 Nov 07	10 Apr 08	10 Dec 08	9 Apr 09	20% of total N fertiliser
Floodwater sampling, pH and temperature measurement	30 Nov 10 Dec 07	10-20 Apr 08	10-20 Dec 08	9-19 Apr 09	One before and 10 consecutive days after fertiliser application
Soil and plant sampling at tillering	31 Dec 07	1 May 08	2 Jan 09	30 Apr 09	Sampling taken each plot
2nd urea fertiliser applied at tillering stage	1 Jan 08	2 may 08	3 Jan 09	1 May 09	30% of total N fertiliser
Floodwater sampling,pH and temperature measurement	1-11 Jan 08	2-12 May 08	3-13 Jan 09	1-11 May 09	before and 10 consecutive days after fertiliser application
Soil and plant sampling at panicle initiation	14 Jan 08	24 May 08	22 Jan 09	19 May 09	
3rd urea fertiliser applied at panicle initiation stage	15 Jan 08	25 May	23 Jan 09	20 May 09	50% of total urea fertiliser
Floodwater sampling , pH and temperature measurement	15-25 Jan 08	25 May – 4 Jun 08	23 Jan -2 Feb 09	20-30 May 09	before and 10 consecutive days after fertiliser application
Soil and plant sampling at flowering stage	30 Jan-08	09 Jun 08	05 Feb 09	09 Jun 09	
Harvesting	05 Mar 08	16 Jul 08	12 Mar 09	11 Jul 09	

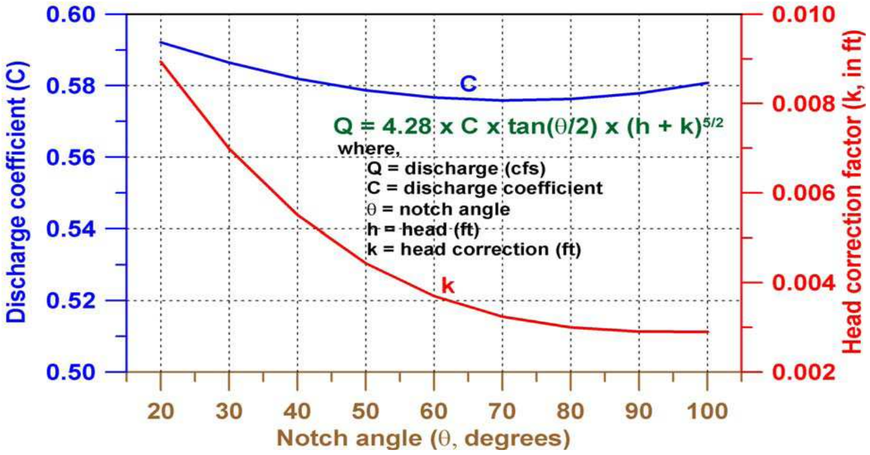

Figure 3.5 Value of discharge coefficient (C) and head correction factor (k) for various notch angles of a V-notch weir (Boman et al., 2008)

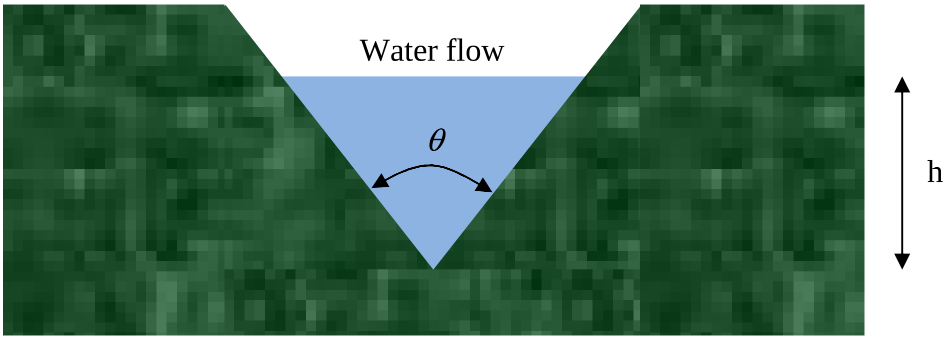

Figure 3.6 A schematic representation of V-notch weir installed in the experimental sites and associated measurements.

For both CS and ASNS irrigation treatments, ponded water depths in the field were maintained between 0 - 2 cm within the first 7 days after transplanting (DAT). After this period, the treatments were introduced. For all plots of CS treatment, Irrigation in each block was applied in the morning to maximum 10 cm and allowed to reach about 0-1cm before re-irrigation. When water input from rainfall exceeded above the maximum ponding depth, the plots were drained to the desired water depth and regarded as surface runoff. The quantity of surface runoff in both CS and ASNS plots was estimated by subtracting rainfall with maximum ponding depth of each CS and ASNS treatment.

For all plots under the ASNS treatment, maximum ponding depth of 5 cm was achieved and any excess rainfall was drained to maintain the desired ponding depth within the plot during rice growth period. ASNS plots remained without submergence 4-6 times for approx. 5–7 days depending on antecedent rainfall. During this period, water depth was allowed to drop down to 10 cm below the soil surface although the soil remained saturated before re-irrigation.

The depth of ponding was measured daily in the morning during the rice growth period using PVC stand pipes (15 cm diameter and 40 cm long) which were installed in each plot to a depth of 20 cm below the soil surface (Fig. 3.7). The bottom of the pipe was sealed was an end cap and was perforated with approx. 0.5-cm diameter holes at spacing of 2-cm on the side at the bottom of the pipe. During non-submergence period in ASNS plots, the depth of water level reaching below soil surface was also recorded from inside the pipes.

Figure 3.7 PVC pipes installed at all experimental plots to measure daily ponding depth and water depth below soil surface.

The ground water table at the experimental site was measured daily using a well located 20 m from the experimental site. A long ruler was installed inside the well up to the soil surface and the depth of ground water table was recorded daily. The daily percolation rate of experimental sites was measured daily using a covered metal cylinder of 60 cm diameter inserted into soil to a depth of 25 cm. The cylinder was initially filled with water and the difference in water level from the previous day indicated daily percolation rate (Figure 3.8). Floodwater from all plots was drained 10 days before harvesting. McCauley and Way (2002) reported that there was no reduction in yield or milling quality of rice when the field is drained two weeks before harvesting rather than the common practice of draining four weeks after 50% heading.

3.2.6 Pest and weed control

All weeds and pests were controlled in the field experiment. Weeds were removed manually by hand. Carbofuran (carbamate as the active ingredient) was applied at a rate of 2.2 kg ha^{-1} at flowering stage of each season to control the out breaks of rice stem borers (*Scirpophaga incertulas).*

Figure 3.8 Covered metal cylinder installed just outside of the experimental plots for the measurement of daily percolation rates for the experimental site. 1, Cylinder just installed; 2, cylinder covered to minimise evaporation; 3, observing water depth in cylinder.

3.2.7 Sampling and measurements

3.2.7.1 Floodwater sampling

Floodwater of each rice plot was sampled the day before and 10 days after each application of N-fertiliser. Five subsamples of floodwater (100 ml) were collected from each plot and mixed to make a single sample. All floodwater samples were immediately brought to the laboratory and filtered with Whatman filter paper no. 42. The filtrate was analysed for NH_4-N and NO_3-N using the standard methods for examination of water and wastewater as described by Eaton et al. (1995).

3.2.7.2 Soil sampling

Soil was sampled at each stage of rice growth (tillering, panicle initiation, flowering and harvesting) concomitantly with plant sampling. Soil samples were taken from each plot with an augur for 0-20, 20-40, 40-70, 70-100 cm soil depths. The sampled hole was filled with clay from outside of the plots to maintain soil continuity within the plot. Representative subsamples of these soil samples were immediately analysed for NO_3-N and NH_4-N. The remains of the soil samples were air dried for further analyses for total-N and organic carbon. Additional representative soil samples from the experimental site were also collected to characterise physical and chemical properties. These measurements included soil texture, pH, EC, organic carbon, Cation Exchange Capacity (CEC), exchangeable cations (Ca^{+2}, Na^{+}, Mg^{+2} and K^{+}), total-N, NO_3-N, NH_4-N, and Phosphate. These soil properties were reported early in Table 3.1.

Moist soil samples when collected in the field were thoroughly mixed and representative subsamples were extracted immediately in the laboratory by shaking the soil samples with 2 M KCl solution (at a 1:6 soil:water ratio) for one hour on a mechanical shaker. The soil samples were filtered and the extracts were analysed for NH_4–N and (NO_3 + NO_2)-N by a micro-Kjeldahl procedure (Mulvany, 1996). The remainder of the soil samples were air dried for 5-6 days before total-N and organic carbon analysed. Total-N was measured using micro-Kjeldahl procedure following digestion, distillation and titration procedures as described by Mulvaney (1996). Organic carbon of each soil sample was determined following Walkley and Black method as described by Allison (1965). Water content of subsamples in both moist and dried soil samples was estimated to apply correction for soil moisture.

3.2.7.3 Plant sampling

For each rice crop, plant samples were collected four times: tillering (30 DAT), panicle initiation (52 DAT), flowering (66 DAT), and harvesting (100 – 110 DAT). Six hills of rice plants were cut at the ground level and separated into green leaf (blade), dead leaf, stem and panicle (if any) as components of the above ground biomass. Dry weight of each fraction of biomass was recorded after drying samples at 70^{o}C for three days or constant as described by Miller (1998). Total-N concentration of each plant sample was determined using the same method as for total-N of soil. N uptake of rice was estimated as the product of total-N concentration and biomass.

3.2.7.4 Leaf area index

Leaf area index (LAI) for rice was estimated using the direct method described by Breda (2003). A leaf area meter (Model CI-202, CID Bio-Science, Inc., USA) was used to measure leaf area of the green leaf fraction of plant biomass. Specific leaf area (SLA) was calculated by dividing leaf area by the dry mass of the green leaf sample. LAI was estimated by multiplying SLA by the total dry mass of leaves over a known ground area.

3.2.7.5 Yield and productivity

A 2 m × 2 m area within each plot was used to estimate grain yield in kg ha^{-1} at 14% grain moisture content. Previous biomass sampling locations in all plots were avoided for accurate measurement of yield. From the 6-hills within the sampled area, grain samples were dried in a convection oven at 70^{o}C for 2 days or to a constant weight for the estimation of 1000 grain weight, grain-N and grain-protein. Grain-N concentration was determined using the same method as for plant total-N. Grain-protein concentration was converted from grain-N concentration to protein by multiplying it with the protein conversion ratio of 5.13 (Mosse, 1990). Nitrogen utilisation efficiency for the crops was computed by dividing the grain mass (kg grain) by the N content of plants (kg N) (Samonte et al., 2006). Water productivity (kg grain m^{-3} water) was calculated as grain yield divided by the total net water input (irrigation + rainfall-runoff) that was summed for the period of transplanting to harvest (Molden, 1997).

3.3 Legume experiment

The experiment with legume was conducted over 2 cropping seasons following the second rice crops during July to November in 2008 and 2009. Peanut (*Arachis hypogaea* L.) cultivar Garuda and soybean (*Glycine max* L. Merr.) cultivar Wilis were immediately planted after the harvest of the second season of rice. The cropping calendar for legumes including growth stages for the field experiment is shown in Table 3.3. The experiment was based on a split-plot design consisting of three replicates of treatment within blocks similar to the experiment with rice. The main treatments, was two irrigation treatments CS and ASNS for rice, were substituted with peanut and soybean crops and the subplot involved three rates of N-fertilisation (referred to as F0, F1 and F2 treatments to indicate 0, 12 and 24 kg N ha^{-1}, respectively).

3.3.1 Soil preparation and legume crops cultivation

The soybean plots were not cultivated as it is common practice in irrigated areas in this region. The peanut plots were ploughed and harrowed prior to peanut sowing. Certified seeds of peanut and soybean were sown with 2 seedlings per hill at a spacing of 30 × 20 cm for soybean and 40 × 20 cm for peanut. Sowing date of each crop in various seasons are given in Table 3.3. Rice straw was returned to each plot as mulch for both peanut and soybean.

For Soybean, phosphorus (P) and potassium (K) fertilisers were applied 10 days after sowing (DAS) at the rates of 75 kg TSP36 per ha and 50 kg KCl per ha, respectively (as locally recommended). Nitrogen fertiliser was applied according to the treatments schedule. N treatments for both soybean and peanut included three rates: 0, 12 and 24 kg N ha^{-1}. For soybean, N treatments were applied as 30% at 10 DAS, and 70% at 30 DAS. For peanut, all N fertiliser treatments, P and K fertilisers were applied at the rates of 100 kg SP36 per ha and 50 kg KCl per ha, respectively (as locally recommended) at10 DAT. Irrigation water was applied to prevent plants from water stress. The amount and time of irrigation was estimated from a lysimeter installed in experimental plots. All weeds and pests were controlled in the field experiment. Weeds were removed manually by hand. Insecticide Decis 1.5EC (Deltamethrin as the active ingredient) was applied at a rate of 150 ml ha^{-1} at 23 and 32 DAS in 2008 and 2009 seasons to control pests during soybean and peanut growth periods.

Table 3. 3 Cropping calendar used for legume crops during the field experiment.

Crop management and sampling activities	2008		2009		Comments
	Peanut	Soybean	Peanut	Soybean	
sowing	19 July 08	19 July 08	19 July 09	19 July 09	Spacing for peanut:40×20 cm; for soybean:30×20cm
Basal and 1st N fertiliser	28 July 08	28 July 08	28 July 09	28 July 09	N fertiliser applied at once for peanut and of 30% of total N fertiliser was applied for soybean
Soil and plant sampling at Vegetative stage	21 Aug 08	21 Aug. 08	20 Aug. 09	20 Aug. 09	Sampling taken each plot
2nd urea fertiliser applied at vegetative stage		22 Aug. 08		22 Aug. 09	70% of total N fertiliser for soybean
Soil and plant sampling at flowering	3 Sep. 08	5 Sep. 08	30 Aug. 09	30 Aug. 09	
Plant sampling			10 Sep. 09	10 Sep. 09	
Plant sampling			20 Sep. 09	20 Sep. 09	
Plant sampling			30 Sep. 09	30 Sep. 09	
Plant sampling			10 Oct. 09	10 Oct. 09	
Harvesting	18 Oct. 08	24 Oct. 08	20 Oct. 09	24 Oct. 09	

3.3.2 Plant sampling

For each plot, plant samples were collected three times coinciding to the key growth stages of the crop. These included vegetative stage (30 DAS), reproductive stage (flowering: 45 and 48 DAS for peanut and soybean, respectively) and harvesting stage (91-93 DAS and 97 DAS for soybean and peanut, respectively). About 8-hill and 6-hill plant samples for soybean and peanut, respectively were taken from sample areas of 0.50 m^2 to determine crop biomass, leaf area index and total-N crops. The sampling and measurement procedures for these crops were similar to that for the rice crop.

Soybean and peanut crops were harvested at physiological maturity and yield recorded at 11% moisture content. A 3 m × 2 m and 4 m×2 m area within each plot for soybean and peanut respectively were used to sample grain yield and converted to kg ha^{-1}. In the 2009 legume crop season, additional plant samples were collected at 10-day intervals to estimate biomass and number and weight of root nodules.

3.3.3 Soil sampling

Soil was sampled at each growth stage of peanut and soybean, the same times with plant sampling that coincided with the vegetative, reproductive and harvesting stages. The soil sampling and measurement procedures for the legume seasons were similar to that for the rice crop.

3.3.4 Nodulation

The root systems of three hills of plants collected from each plot were gently taken using a core barrel (8 cm in diameter) to a depth of 20 cm. Samples were washed gently with water to remove soil. Root nodules were counted for each plant, air dried and weighted. Root nodule samples were collected at vegetative, flowering, pod filling, full pod fill and full seed growth stages for both peanut and soybean.

3.4 Statistical analysis

Most data were subjected to analysis of variance (ANOVA) with irrigation or legume crops as mean plot treatment and N treatments as sub- plot treatments using the Genstat Software (Version 9.2.0.153, VSN International Ltd, Oxford). When one or more treatments had a significant effect on a measured parameter, least significant difference (LSD) was calculated to compare mean values of treatments.

CHAPTER IV

Growth and yield of lowland rice on coarse soils in response to water-saving irrigation and nitrogen management strategies

4.1 Introduction

Rice is the staple food crop in Asia occupying 135 million hectares of land, over half of which is irrigated (Calpe, 2001; FAO, 1999; Kennedy et al., 2002). Since there has been a global decline in harvested area for rice during 1999 to 2005 (FAOSTAT, 2005) and a growing need for rice to feed 4000 million people (Greenland, 1997) by 2015, there is an ever-increasing need and challenge to increase rice productivity. The possibility for expanding the area under rice-based farming systems is also limited due to increased competition for land and water from the urban and industrial sectors with the population growth within the major rice producing nations (Nguyen, 2006; Tuong and Bhuiyan, 1999).

Most of the soils used to grow lowland rice (also referred to as *paddy*) have fine texture with low percolation rates that allow extended periods of submergence. These soils become anaerobic when submerged (flooded) that reduces nitrification allowing accumulation of NH_4–N essential for growing lowland rice (De Data, 1995). However, with increasing demand for rice and other crops to support the growing population within major rice growing nations, coarse-textured soils are being used increasingly for both upland and lowland irrigated rice (Aulakh and Bijay-Singh, 1997; Aulakh and Pasricha, 1997). It is difficult to maintain flooding in coarse-textured soils over a long period due to inherently high soil permeability leading to high water percolation rates. Development of appropriate irrigation strategies to maintain rice production with available water resources within the agricultural sector is a high national and global priority as rice production needs to increase by 70% over the current production levels by 2025 (Tuong and Bhuiyan, 1999).

Conventional water management in lowland rice is aimed at maintaining continuously submerged (CS) conditions from transplanting to crop maturity. Water and nitrogen managements in eastern Indonesia are generally similar to any other rice growing region in SE-Asia. Continuous submergence and broad application of N fertiliser at the farmer's recommended rate is a general practice throughout the region. More rigorous examination of this practice is needed including comparing it to alternative practices such as maintaining intermittent nonsubmerged conditions over several days throughout the growing season (Bouman and Tuong, 2001). Systems of alternate submergence-nonsubmergence (ASNS; also known as alternate wetting and drying, AWD) conditions have been reported to maintain or even increase yield of rice in some parts of China (Li, 2001; Mao, 1993). However, similar benefits of ASNS systems have not been observed in the Philippines, India or Australia when compared with CS systems (Heenan and Thompson, 1984; 1985; Mishra et al., 1990; Tabbal et al., 2002; Tripathi et al., 1986). The success of ASNS systems possibly depends on other environmental conditions, such as soil type, depth to groundwater, the timing and duration of nonsubmerged condition, the nature of the rice cultivar, and crop management aspects including nitrogen fertilization (Bouman and Tuong, 2001; Tabbal et al., 2002, Tuong et al., 2005). Most of the experiments with ASNS systems have been conducted on clayey soils with a shallow ground water table. However, the hydrological and environmental conditions of coarse soils under which current and future rice-based cropping systems might be located is limited. Further studies will extend our knowledge of the response of rice-based irrigated cropping systems to coarse textured soils where the competition for land with urban and industrial sectors is high.

When rice is grown in areas with fine textured soils (e.g. silty clay loam) and shallow water tables (within 0.5 m from soil surface), rice yield with alternately submerged and non-submerged (ASNS) irrigation regimes is either similar or slightly lower than continuously submerged (CS) irrigation regimes (Belder et al., 2004). In this situation, with ASNS type of irrigation regime, rice is not exposed to significant water stress due to capillary contribution from the shallow water table (Tuong et al., 2005). However, in areas with a deep water table and coarse textured soils, reduced capillary contribution of the water table to water used by the rice crop may reduce yield for ASNS water regime compared to CS. Soil water deficit within the crop's root zone also contributes to yield reduction. A soil water potential <-20 kPa within the top 10 cm depth has been reported to reduce yield significantly (Cabangon et al., 2003) while no adverse impact on yield was observed when the soil water potential within 15-20 cm depth was maintained within -8 to -16 kPa (Hira et al., 2002). The aim of this study was to compare the relative effectiveness of ASNS and CS irrigation practices in maintaining productivity when it is combined with various N-fertilizer rates on a coarse soil with deep water table in the tropical region of eastern Indonesia using four rice growing seasons from October 2007 to July 2009.

4.2 Materials and methods

Full details of the field experiments related to this study are described in Chapter 3. Essential aspects of the experiment are briefly discussed below. The experiment consisted of a randomised split plot design with two irrigation treatments: CS and ASNSas main plot and three nitrogen fertiliser rates (0, 70 and 140 kg N ha^{-1} hereafter referred to as F0, F1 and F2 respectively) as subplot treatments with three replications. In plots under the CS water irrigation, the ponding depth was allowed to fluctuate between 0-10 cm throughout the rice growth period, whereas for the ASNS irrigation treatment, the maximum ponding depth was 50 cm. Water irrigation was applied to maximum ponding depth in the morning when water depths were close to zero. Any rainfall occurring above maximum ponding level was drained during the growth period of rice. Plots under the ASNS treatment remained without submergence for around 5–7 days for 4-6 times during the growth period, depending on the amount and rainfall received. During this period, water ponded depth was allowed to drop down to 10 cm below the soil surface..

The field experiment was conducted during October 2007 to July 2009 which consisted of two wet and dry seasons. First rice was planted in the wet season (transplanted on 23rd November 2007 and harvested on 5th March 2008). Plant and soil samples were taken at four main phenological stages of rice (tillering, panicle initiation, flowering and harvesting). Soil samples of four soil layers (0-20, 20-40, 40-70 and 70-100 cm) were analysed for NH_4-N, NO_3-N, total-N, and organic carbon (OC). Plant samples were measured for dry biomass and the concentration of total-N. At harvesting stage, rice plants were sampled in an area of 100 m^2 to obtain grain yield, which was converted to kg of grain yield ha^{-1} and presented at 14% grain water content. The second rice crop was transplanted at approximately one month after first harvest of the first rice crop at the end of the wet season, coinciding with the dry season (transplanted on 1st April 2008 and harvested on 16th July 2008). All cultural practices and sampling procedures were similar to the first rice season. The cultural practices and sampling procedures were repeated for these seasons in the following year (2008-2009). All data were analysed with the Genstat software (Version 9.2.0.153, VSN International Ltd, Oxford).

4.3 Results

4.3.1 Weather

Average daily weather data (minimum and maximum temperature, radiation and rainfall) during rice growth seasons are presented in Table 4.1. Cumulative rainfall during the wet season of 2007/2008 was more than three times the rainfall received during the dry season of 2008. Similarly, cumulative rainfall during the wet season of 2008/2009 was more than twice the rainfall received during the dry season of 2009. Table 4.1 shows that the climate of the experimental site is typical of a tropical and humid monsoon region and accounts for 70–80% of total annual rainfall during November to March/April. Seasonal year to year variation was changed to seasonal and inter annual variation. Seasonal and inter annual variation in radiation was also small, except that it was much lower during the rice dry season of 2009. However, the long term climate data (Chapter III) shows that radiation in the dry season was higher than in wet season while maximum and minimum temperatures were in a reverse pattern.

Table 4.1 Average radiation maximum and minimum temperatures and total rainfall during the two wet and dry rice growing seasons.

Seasons	Radiation (MJ m^{-2} day^{-1}),	Maximum temperature (°C)	Minimum temperature (°C)	Rainfall (mm)
2007/2008 (wet)	20.1	32.1	24.0	1051
2008 (dry)	22.2	31.5	22.9	298
2008/2009 (wet)	17.3	30.4	23.5	998
2009 (dry)	14.3	31.7	20.5	409

4.3.2 Ground water table

Variation with the daily water table depth over time for the experimental site is presented in Fig. 4.1. In general, the water table remained close to the soil surface at 470 cm during December to June due to the high rainfall during the wet season as described in Table 4.1. The water table dropped rapidly to around 520 cm thereafter from July and remained around a similar depth until mid October. Recovery of the water table after October 2008 could be due to rainfall which occurs usually during November to April. During the dry rice season, irrigation water of the rice field was supplied from an irrigation channel which may have contributed to the water table remaining close to soil surface. Since the irrigation channel was drained at the end of the rice growth period in the dry season (early July), a rapid drop in the depth of the water table to the lowest level principally occurred during the dry seasons.

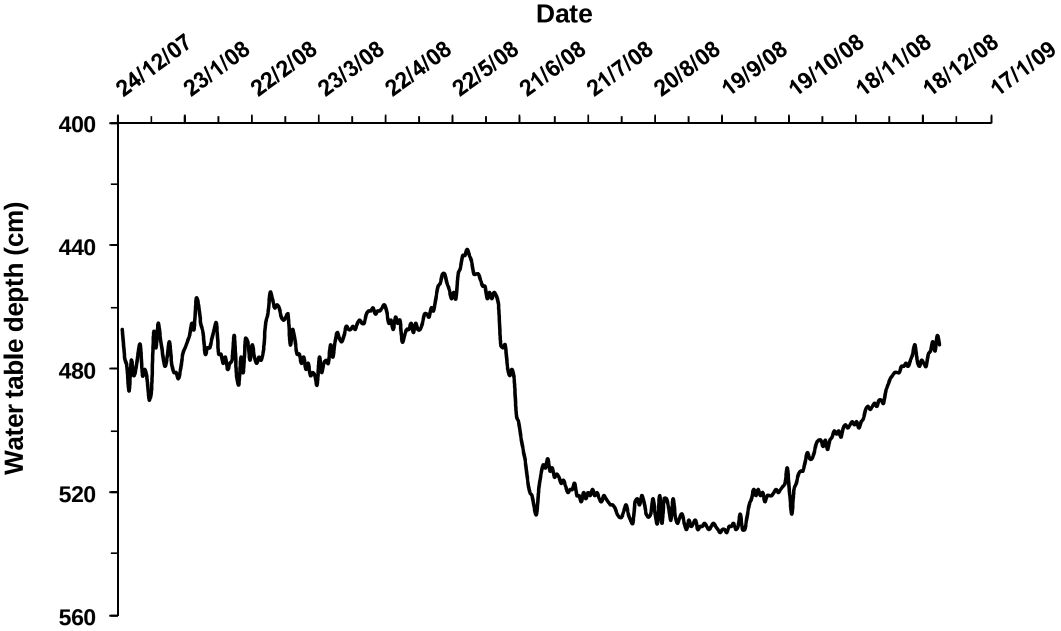

Figure 4.1 Daily fluctuation in groundwater table depth at the experimental site from 23 November 2007 to 31 December 2008.

4.3.3 Flood water dynamics during rice growth periods

Daily variation in ponded water depth and rainfall for CS and ASNS irrigation treatments during the rice growing seasons of 2007-2008 and 2008-2009 are shown in Figs. 4.2 and 4.3, respectively. Ponding depths for both CS and ASNS irrigation treatments remained within 0-2 cm in the first 7 DAT and drained at 10 days before rice was harvested and irrigation treatments introduced between these periods. Water depth varied across rice seasons and irrigation treatments. There was a clear difference in the water regimes between the two irrigation treatments. In the CS irrigation treatment, water depth fluctuated from 0 – 10 cm throughout the rice growing season. In the ASNS treated plots, there were periods without standing water for 5-7 days. Maximum water depth was less than 50 mm during rice growing seasons with minimum water depth of 64 mm, 79 mm, 50 mm, and 99 mm in 2007/2008, 2008, 2008/2009 and 2009 rice growing seasons respectively. In ASNS, water depth dropped below the soil surface to a greater depth in dry seasons than in wet seasons.

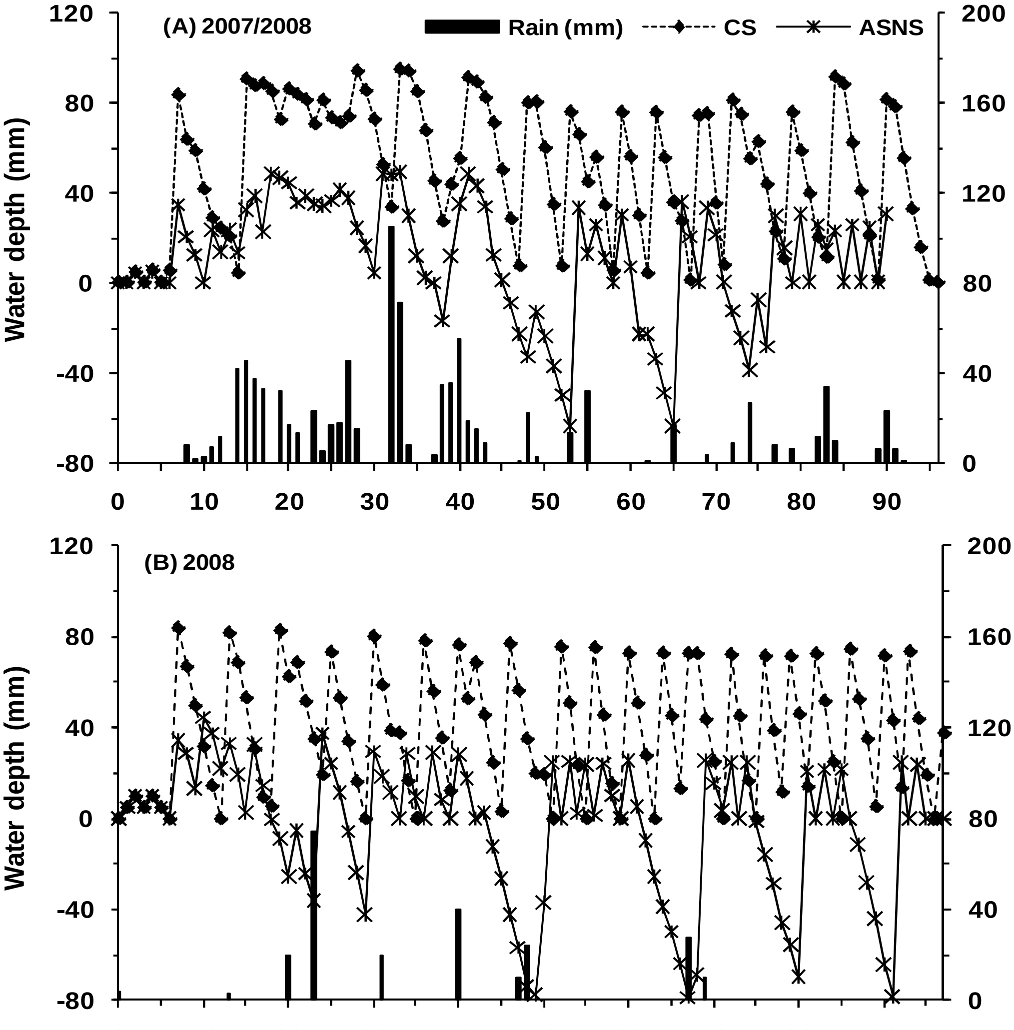

Figure 4.2 Variation in daily water depth and rainfall for CS and ASNS irrigation treatments during 2007/2008 (A) and 2008 (B) rice growing seasons. Negative value of water depth indicates presence of water level below soil surface.

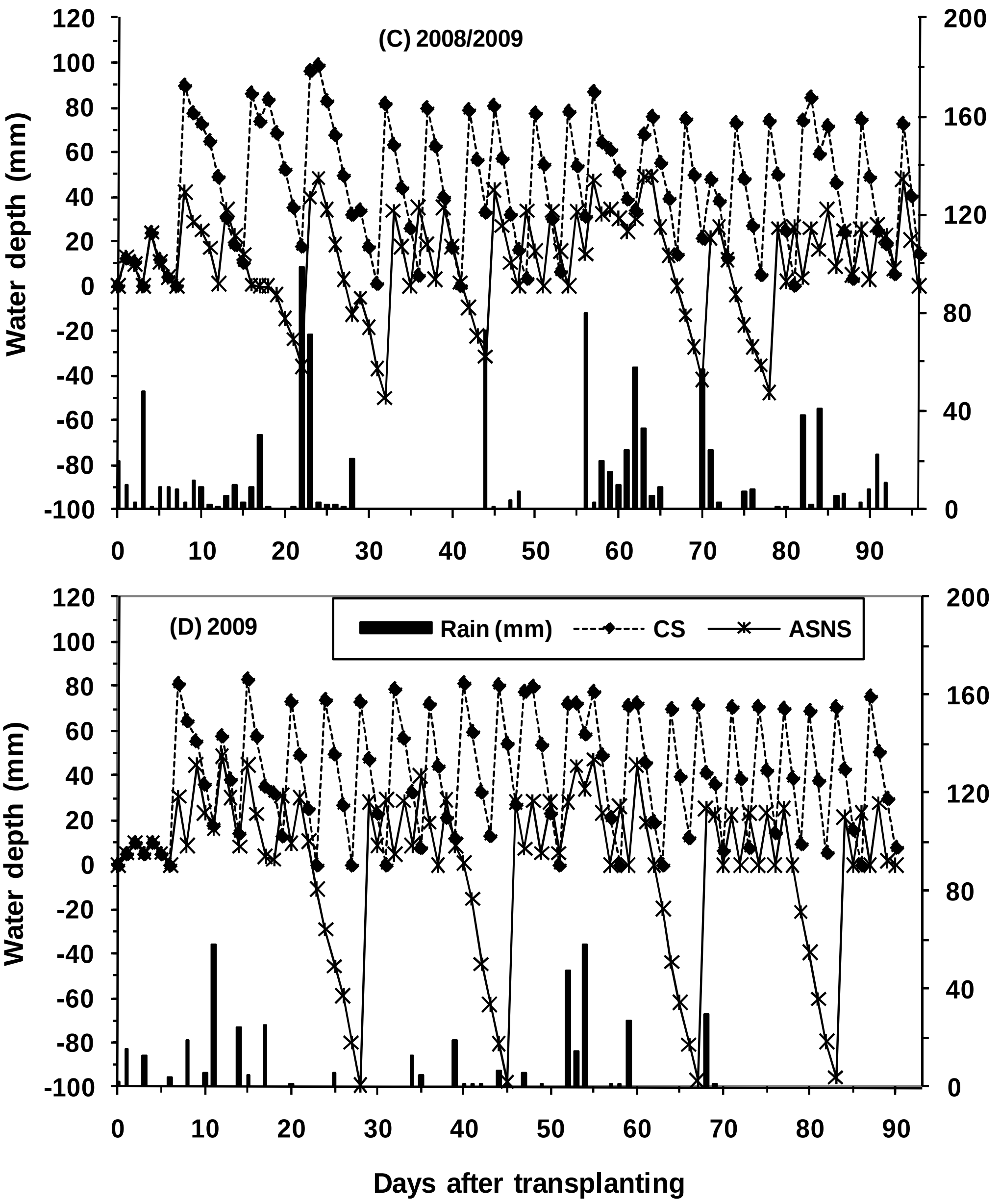

Figure 4.3 Variation in daily water depth and rainfall for CS and ASNS irrigation treatments during 2008/2009 (C) and 2009 (D) rice growing seasons. Negative value of water depth indicates presence of water level below soil surface.

Total water input during the wet seasons (2007/2008 and 2008/2009) was always higher than during the dry seasons (2008 and 2009) (Table 4.2) which was probably due to higher rainfall during the wet season than during the dry season. At all times, water input from irrigation was higher under CS than under the ASNS. Furthermore, percentage of days without ponding water in the ASNS treatment was higher in dry seasons than in wet seasons. Total water input into plots from irrigation and rainfall during the four growing seasons of rice ranged from 2053 to 2272 mm for CS and from 1335 to 1590 mm for ASNS. These differences allowed irrigation water to be saved in the range of 36 – 44% with ASNS compared to CS irrigation regimes during 2007-2009. When combined with water captured from rainfall during the growing seasons, there was water saving of 23% to 35% during the four rice seasons. Mean percolation rate during 2007-2008 growing seasons was around 10.4 mm and increased further to 17.1 mm day^{-1} during 2008-2009 growing seasons (details not given).

Table 4.2 Water input for CS and ASNS irrigation treatments and water saved and days without ponding for ASNS during four rice growing seasons (2007-2009).

Water input	2007/2008		2008		2008/2009		2009	
	CS	ASNS	CS	ASNS	CS	ASNS	CS	ASNS
Rainfall (mm)*	1051	1051	298	298	998	998	409	409
Net rainfall (R, mm)#	1046	940	233	233	965	849	409	392
Irrigation (I, mm)	1080	690	1820	1102	1234	689	1864	1198
Total water input (I+R)	2126	1630	2053	1335	2199	1538	2272	1590
Irrigation water saved with ASNS (%)		36		39		44		36
Total water saved with ASNS (%)		23		35		30		30
Days without ponding water in ASNS		22		35		28		32

*, total rainfall during rice growth period; #, net rainfall retained within plots

4.3.4 Water productivity at various irrigation and N fertiliser treatments

Both irrigation treatments and N fertiliser application rates, and their interactions had a significant effect on water productivity of rice in all rice growing seasons (Table 4.3). The influence of irrigation treatments and N fertiliser application rates on water productivity over four rice growing seasons is presented in Fig. 4.4. Water productivity based on total water input (irrigation+rainfall) was highest with the ASNS and F2 combination of irrigation and N fertiliser treatment. Water productivity increased significantly as nitrogen fertiliser application increased.

Table 4.3 Variation in water productivity of rice as affected by various irrigation treatments (I) and N fertiliser application rates (F) during four seasons. CS is continuously submerged; ASNS is alternately submerged and non-submerged; F0, F1 and F2 indicate the application of 0, 70 and 140 kg N ha^{-1}, respectively; *, ** and * indicate significant effects at P = 0.05, 0.01 and 0.001, respectively**.

Irrigation (I)	Fertiliser (F)	water productivity of rice (kg grain m^{-3}water)			
		2007/2008	2008	2008/2009	2009
	F0	0.189	0.179	0.176	0.115
CS	F1	0.295	0.252	0.275	0.153
	F2	0.369	0.302	0.343	0.188
	F0	0.244	0.251	0.257	0.175
ASNS	F1	0.382	0.356	0.385	0.233
	F2	0.475	0.433	0.482	0.286
	Main plot (I)	**	***	*	**
F-test	Subplot (F)	***	***	***	***
	I×F	**	*	*	*

Water productivity in the ASNS treatment was significantly higher than that in CS treatment at given level of N fertiliser treatment. The mean water productivity ranged from 0.11 to 0.37 kg grain m^{-3} water and 0.25 to 0.48 kg grain m^{-3} water for CS and ASNS, respectively. Water productivity based on irrigation input was higher than based on total water input, ranging from 0.13 to 0.73 kg grain m^{-3} water for CS and 0.22 to 1.12 kg grain m^{-3} water for ASNS. Water productivity during the wet seasons (2007/2008 and 2008/2009) was slightly higher than during the dry season (2008 and 2009), probably due to less irrigation applied (Table 4. 3) and higher grain yield in the wet season than in the dry season (Table 4.5).

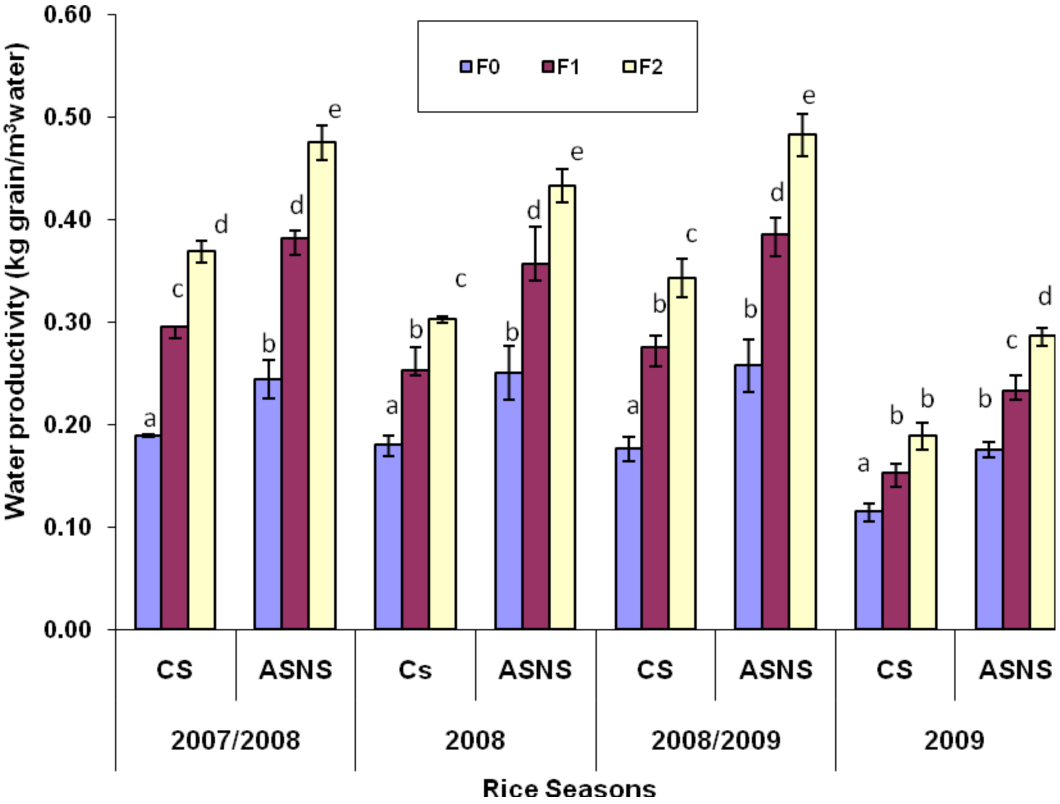

Figure 4.4 The effects of irrigation treatments (CS and ASNS) and N fertiliser application rates (F0, F1 and F2) on water productivity over four rice growing seasons. For specific water productivity component, similar letter(s) for a given season (2007/2008, 2008, 2008/2009 and 2009) indicate the difference between mean values to be less than LSD. LSD values for the interaction of irrigation×nitrogen on water productivity for four consecutive seasons were 0.02, 0.04, 0.02 and 0.02 kg grain m^{-3} water. Vertical bars indicate SE (n = 3).

4.3.5 Nitrogen uptake

The effects of water and N fertiliser treatments on nitrogen uptake in four rice growing seasons are presented in Table 4.4. N uptake was significantly influenced by nitrogen fertiliser but not by irrigation treatments. There was also no interaction effect of N fertiliser and irrigation treatments on N uptake. Nitrogen uptake significantly increased as nitrogen fertiliser rates increased. In CS, nitrogen uptake ranged from 47 to 69 kg N ha^{-1}, 83 to 111 kg N ha^{-1} and from 140 to 163 kg N ha^{-1} for no fertiliser, 70 kg N ha^{-1} and 140 kg N ha^{-1}, respectively. In ASNS, nitrogen uptake ranged from 44 to 66 kg N ha^{-1}, 90 to 109 kg N ha^{-1} and from 139 to 162 kg N ha^{-1} for no fertiliser, 70 kg N ha^{-1} and 140 kg N ha^{-1}, respectively. Although nitrogen uptakes were higher in CS than in ASNS, the difference was not statistically significant. Nitrogen uptake was higher during the wet season (2007/2008 and 2008/2009) than during the dry seasons (2008 and 2009).

Table 4.4 Variation in N-uptake of rice as affected by various irrigation treatments (I) and N fertiliser application rates (F) during four seasons of rice growth. . CS is continuously submerged; ASNS is alternate submerged and non-submerged; 0, 1 and 2, are 0, 70 and 140 kg N ha^{-1} respectively; values in the bracket are standard deviation. *, ** and * indicate significant at P = 0.05, 0.01 and 0.001, respectively. NS = not significant at P > 0.05.**

Irrigation (I)	Fertiliser (F)	N-uptake (kg N ha^{-1})			
		2007/2008	2008	2008/2009	2009
CS	F0	68.8 (12)	49.5 (3)	58.2 4)	47.3 (5)
	F1	111.2 (2)	82.9 (4)	107.7 (4)	96.6 (4)
	F2	163.8 (4)	152.4 (6)	157.0 (12)	140. (5)
ASNS	F0	65.7 (5)	47.1 (6)	53.1 (4)	44.2 (4)
	F1	109.4 (3)	91.1 (8)	98.7 (5)	90.4 (13)
	F2	162.0 (11)	142.8 (5)	146.7 (7)	138.7 (5)
F-test	Main plot (I)	NS	NS	NS	NS
	Subplot (F)	***	***	***	***
	I×F	NS	NS	NS	NS

4.3.6 Crop growth and development

The effects of irrigation and nitrogen fertiliser treatments on above ground biomass at different phenological stages of rice over four growing seasons are shown in Fig. 4.5. Irrigation treatments did not significantly affect biomass accumulation during development of the rice crop in any of the four rice seasons studied. Biomass in each phenological stage of rice increased as N fertiliser application rates increased. In all rice growing seasons, the crop matured 4-5 days earlier in F0 than in F1 and F2 N treatments. In most cases, above ground biomass was higher in CS than in ASNS during all rice seasons, although this difference was not statistically significant. Above ground biomass was higher in wet seasons (2007/2008 and 2008/2009) than in the dry season (2008 and 2009).

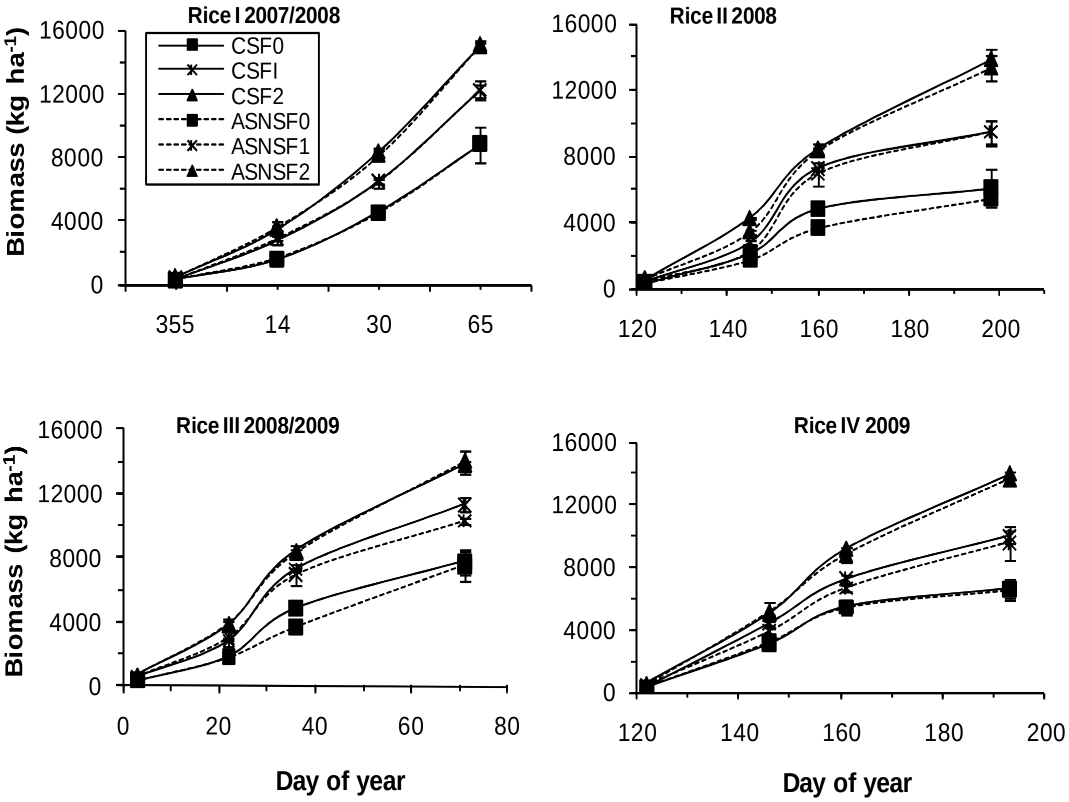

Figure 4.5 Effects of irrigation treatments (CS and ASNS) and nitrogen fertiliser rates (F0, F1 and F2) on above ground biomass at various stages of growth during four rice growing seasons of 2007/2008, 2008, 2008/2009 and 2009.

The effects of irrigation treatments and N fertiliser on leaf area index (LAI) at various growth stages of rice over four growing seasons are shown in Fig. 4.6. Nitrogen fertiliser application rates significantly influenced LAI in each phenological stage of plant growth regardless of irrigation treatments. Mean LAI ranged from 0.7 to 3.0 for F0, 0.9 to 5.6 for F1 and from 1.3 to 7.0 for F2. The highest LAI was found at the flowering stage in the F2 treatment during the 2007/2008 rice growing season. LAI was higher in CS than in ASNS treatments during panicle initiation and flowering stages in the F2 for all rice growing seasons except for 2007/2008 season, although the differences were statistically not significant. In most cases, LAI in the CS irrigation treatment was higher than in the ASNS irrigation treatments at lower N fertiliser application rates (F0 and F1) during the flowering stage in all rice growing seasons except for F0 during 2008/2009 season.

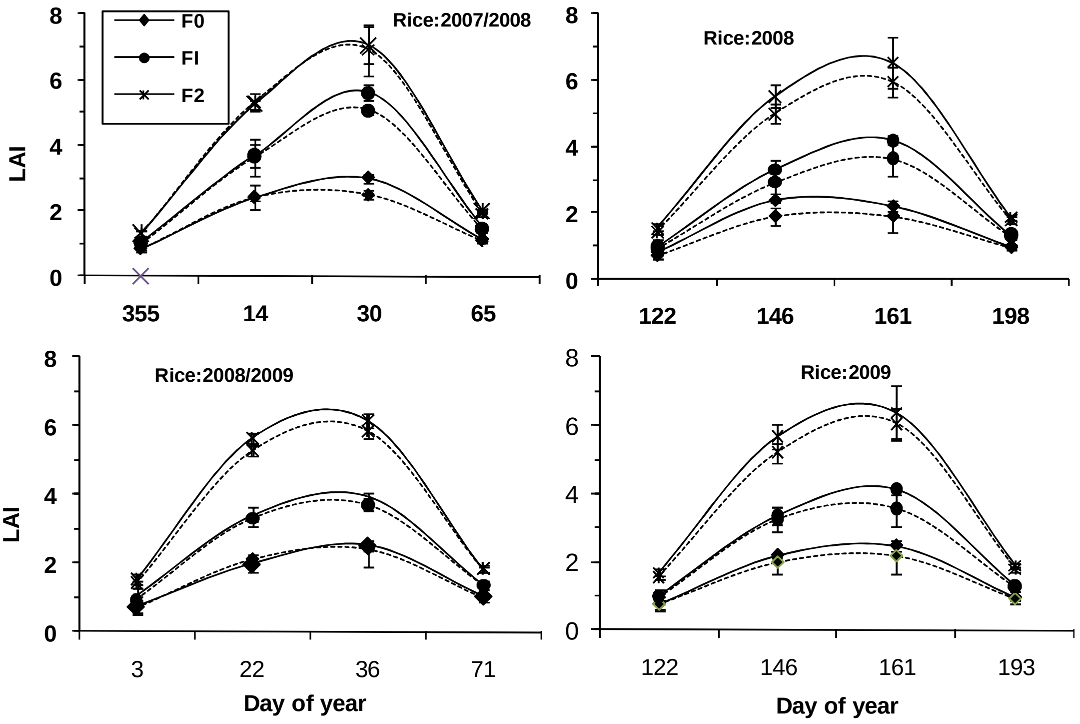

Figure 4.6 Effects of irrigation treatments (CS and ASNS) and nitrogen fertiliser rates (F0, F1 and F2) on leaf area index at different stages of rice growth in four rice growing seasons.

4.3.7 Yield and grain quality

Rice yield (expressed at 14% of moisture content) and 1000 grain weight for various nitrogen fertiliser and irrigation treatments over four rice growing seasons are presented in Table 4.5. Large variation in grain yield was mainly due to yield responses to various treatments. Both rice yield and 1000 grain weight of rice significantly increased as N fertiliser application rates increased, but not by irrigation treatments. Grain yield ranged from 3550 to 4025 kg ha^{-1}, 5042 to 6287 kg ha^{-1} and 5833 to 7842 kg ha^{-1} in F0, F1 and F2, respectively regardless of irrigation treatments. Grain yield during the wet season was higher than during the dry season. There was no interaction effect of irrigation treatments and N fertilisation on rice yield and 1000 gram weight of rice. Rice yield in SC was slightly higher than that in ASNS for about 1 to 5% during the four rice growing seasons although these differences were not significant. However, total water input in ASNS was significantly lower than in CS in all rice growing seasons (Table 4.2).

Table 4.5 Effects of irrigation treatments (I) and nitrogen fertiliser application rates (F) on grain yield and 1000 grain weight in four rice growing seasons. CS = continuously submerged; ASNS = alternate submerged and non-submerged; 0, 1 and 2, = 0, 70 and 140 kg N ha^{-1} respectively; *, ** and * indicate significant at P = 0.05, 0.01 and 0.001, respectively; NS = not significant at P > 0.05.**

Irrigation (I)	Fertiliser (F)	Yield (kg ha^{-1})			
		2007/2008	2008	2008/2009	2009
CS	F0	4025.0	3683.3	3875.0	3750.0
	F1	6266.7	5175.0	6041.7	5000.0
	F2	7841.7	6208.3	7541.7	6166.7
ASNS	F0	3975.0	3550.0	3958.3	3583.3
	F1	6225.0	5041.7	5916.7	4750.0
	F2	7741.7	6133.3	7416.7	5833.3
F-test	Main plot (I)	NS	NS	NS	NS
	Subplot (F)	***	***	***	***
	I×F	NS	NS	NS	NS

Irrigation (I)	Fertiliser (F)	1000 grain weight (gram)			
		2007/2008	2008	2008/2009	2009
CS	F0	23.1	26.4	27.2	26.7
	F1	25.0	27.5	28.6	27.5
	F2	25.3	28.6	29.1	28.2
ASNS	F0	22.9	26.7	27.3	26.6
	F1	25.0	27.7	29.1	27.5
	F2	25.4	28.4	29.6	28.3
F-test	Main plot (I)	NS	NS	NS	NS
	Subplot (F)	**	*	**	**
	I×F	NS	NS	NS	NS

The effects of irrigation treatments and N fertiliser application rates on total grain-N and protein content of rice are presented in Table 4.6. There was a significant effect of N fertiliser treatments on total N concentration in grain and protein content of rice on four growing seasons of rice. Total grain-N and protein contents increased as N fertiliser application rates increased. The interaction of irrigation treatments with N fertiliser had no significant effect on either total N concentration in grain or protein content of grain. Although grain-N and protein content of grain tended to be higher under CS than under ASNS irrigation treatments, the differences were not significant and total grain-N and protein content tended to higher in the wet season than in the dry season.

Table 4.6 Variation in protein contents and total grain-N of rice as affected by irrigation treatments (I) and N fertiliser application rates (F) for four rice growing seasons. CS = continuously submerged; ASNS = alternate submerged and non-submerged; F0, F1 and F2, = 0, 70 and 140 kg N ha^{-1} respectively; *, ** and * indicate significance at P = 0.05, 0.01 and 0.001, respectively; NS = not significant.**

Irrigation (I)	Fertiliser (F)	Protein (%)			
		2007/2008	2008	2008/2009	2009
CS	F0	5.77	6.32	6.59	6.07
	F1	6.50	7.42	7.03	7.32
	F2	7.16	8.42	7.74	8.91
ASNS	F0	5.7	5.98	6.43	5.74
	F1	6.17	7.33	7.13	7.20
	F2	7.01	8.10	7.65	8.49
F-test	Main plot (I)	NS	NS	NS	*
	Subplot (F)	***	***	***	***
	I×F	NS	NS	NS	NS

Irrigation (I)	Fertiliser (F)	Total grain-N (%)			
		2007/2008	2008	2008/2009	2009
CS	F0	0.97	1.06	1.11	1.02
	F1	1.09	1.25	1.18	1.23
	F2	1.20	1.41	1.30	1.50
ASNS	F0	0.96	1.01	1.08	0.96
	F1	1.04	1.23	1.20	1.21
	F2	1.18	1.36	1.29	1.43
F-test	Main plot (I)	NS	NS	NS	*
	Subplot (F)	***	***	**	***
	I×F	NS	NS	NS	NS

4.4 Discussion

The study has clearly shown that the use of alternative submerged and non-submerged (ASNS) irrigation in coarse soils did not result in unusually dry soil conditions as compared to the continuously submerged (CS) irrigation system. The impact of ASNS on yield and yield components was minimal and did not significantly differ from the CS treatment. However, average water saved with ASNS ranged from 36% to 44% compared with CS.

The differences in yield and yield components were significant with various N application rates without a strong influence of irrigation treatments. This is consistent with previous studies of Belder et al. (2004), Bouman and Tuong (2001) 5and Qi Jing et al. (2007). Although surface ponding of water in the ASNS varied considerably from the CS irrigation treatment, the soil remained close to saturation condition as the level of water did not drop 10 cm below the soil surface (Figure 4.2) before the next irrigation was applied. Bouman and Tuong (2001) argued that drought effects in lowland rice can occur when soil water content drops below the saturation level. Results from this study were found to be similar to the studies of Belder et al. (2004) for a soil of high clay content (silty clay) with percolation rates of 1-4.5 mm per day and a shallow ground water table. They reported LAI in ASNS water regime was lower than that in CS at the panicle initiation and flowering stage at the N level of 180 kg/ha. This reduction was thought to be due to reduced leaf expansion as a result of reduced soil water potential from 0 to -10 kPa. Result of this experiment also showed LAI under ASNS to be lower than under CS at panicle initiation and flowering stages with N supplied at the rate of 140 kg ha^{-1}, but these were not significantly different. This indicates that leaf expansion and its effect on yield may not be as significant as previously thought by allowing soil water content to drop below saturation level during non submergence periods. This is supported by studies of Lu et al. (2000) who reported significant decrease in LAI when soil water potential dropped down to -10 kPa under ASNS irrigation treatment without significantly affecting dry matter biomass and grain yield. Similar results have been reported for soil of heavier textures, e.g. silty clay loam (Cabangon et al., 2001). Although the soil at this experimental site was of light texture i.e. sandy loam in the top of 40 cm depth and sandy soil layer below 40 cm depth, there was a hardpan layer within 20-30 cm depth that might have contributed to reducing percolation rates.

4.5 Concluding remarks

This study indicates that the ASNS treatment on coarse soil could result in a water saving of 36-44% compared with CS treatment without significantly reducing biomass, yield and components of yield. Mean water productivity in the ASNS was 52% higher than that in the CS irrigation treatment. Success in the ASNS treatment in maintaining soil moisture close to saturation without significant interactive effects with N-treatments, suggest that these results may be considered as typical for well-drained soils with deep ground water tables, irrigated lowlands in eastern Indonesia.

CHAPTER V

Nitrogen dynamics in rice-based cropping systems under irrigation and nitrogen fertiliser management practices

5.1 Introduction

Nitrogen is one of the most critical nutrient elements limiting growth in most rice-growing soils around the world (Smil, 1999). Improved understanding of the availability of N from the native organic N sources and the fate of added N fertiliser should aid in developing innovative N management practices and an increase in the efficiency of fertilizer (De Datta, 1995). Nitrogen uptake patterns in rice over the growing season depend on the availability of N from soil and fertiliser sources (Bufogle et al., 1997) and can increase significantly with fertiliser application (Guindo et al., 1994) and increasing amount of fertiliser N available (Bufogle et al., 1997).

In most of the tropical rice lowlands including eastern Indonesia, rice is planted once or twice during early wet to early dry seasons in continuously flooded condition. Furthermore, farmers sometimes plant three rice crops each year in the same field when irrigation water is available (Cassman and Pingali, 1995). Optimal productivity of such an intensive rice production system is dependent on relatively large inputs of inorganic N-fertiliser as grain yield is closely correlated with N uptake (Cassman et al., 1993). Despite the importance of N-fertiliser with productivity, the amount of N fertilizer applied by farmers and the native soil-N supply are not well matched. This imbalance contributes to low N fertiliser use-efficiency in these production systems (Cassman et al., 1996; Olk et al., 1999).

Common soil management practices that affect N cycling in these cropping systems are the incorporation of crop residues in puddled soil under mostly anaerobic conditions, repetitive cropping in flooded soil with or without an upland crop rotation, or fallowing soil drying during a week to three months between rice crops. Long-term experiments indicate that continuous cropping of irrigated rice may cause a decline in soil N supply over time although soil organic carbon and total soil nitrogen are conserved or even increased occasionally (Cassman et al., 1995; Dobermann et al., 2000).

Following the harvest of second season of rice, the field usually reverts to dry, aerobic condition after a prolonged period of anaerobic conditions during the growth of two rice crops. During the dry season, the fields are usually planted with legumes such as soybean, peanut, maize and green bean as cash crops. Rotation with some legume crops in aerated soil conditions together with tillage are likely to influence C and N cycling, particularly N availability. However, information on the magnitude of these effects for irrigated lowland rice systems is not well documented (Cassman et al., 1998).

The behaviour of soil nitrogen under wet soil conditions of lowland rice is markedly different from its behaviour under dry soil conditions. Under anaerobic conditions during flooding, the soil tends to accumulate NH_4-N and instability of NO_3-N, results in less N for organic matter decomposition, less efficient in using applied N, amoniacal-N fixation by clays and loss of N via volatilisation, leaching, seepage and nitrification (De Datta, 1995).

Under flooded conditions, most N is available to rice to be taken up is ammonium form. Under alternate submerged and non-submerged (ASNS) conditions, nitrate can be formed during non-submerged periods. Tabbal et al. (1992) showed that the level of ammonium in the soil was lower, and that of nitrate was higher in ASNS than in flooded rice fields. Upon subsequent submerged conditions, nitrate could be leached or undergo denitrification losses making total N losses to be higher under ASNS than under conventional flooding. In contrast, Belder et al. (2004) found N uptake and recoveries were similar under flooded and ASNS conditions when the experiment was conducted under the influence of shallow groundwater tables that kept the soil relatively wet during non-submerged periods. However, there is limited information on nitrogen dynamics when the soil is fully or partly submerged for some time and the soil remains mainly saturated during the nonsubmergence periods in coarse-textured soils with a relatively deep groundwater table. Further research is needed to determine the level of “dryness” in ASNS that does not reduce N-use efficiency (Tuong et al., 2005).

The objective of this study was to evaluate the effects of irrigation and N fertiliser management practices on the dynamics of nitrogen (NH_4-N and NO_3-N) during rice growth over two years as part of the rice-rice-legume crop sequences in the tropical environment. There is also a need to capture N dynamics in order to test the ability of the models to incorporate the related processes.

5.2 Materials and methods

Full details of the materials and methods related to this study are given in Chapter 3. In brief, the field experiment was conducted on a sandy loam soil at an irrigated rice field of the Research Station of Assessment Institute for Agricultural Technology NTB Lombok Indonesia. Two irrigation treatments (continuously submerged and alternate submerged and non-submerged, hereafter referred to as CS and ASNS, respectively) and three nitrogen fertiliser rates (0, 70 and 140 kg N ha^{-1} hereafter referred to as F0, F1 and F2 respectively) were arranged in a randomised split plot design as main plot and subplot respectively with three replications. The field experiment was conducted during October 2007 to July 2009 involving two wet- (October - March) and two dry-seasons (April – July). First rice was planted in wet season (transplanted on 23rd November 2007 and harvested on 5th March 2008).

Ponding depth under the CS irrigation treatment was allowed to fluctuate between 0-10 cm throughout the rice growth period. In the ASNS irrigation treatment, maximum ponding depth was 5 cm and any rainfall occurred above that level during rice growth was drained and remained without submergence for around 5–7 days for 4-6 times during the season. During this period, water level was allowed to drop down to 10 cm below the soil surface before re-irrigation took place. Floodwater of each rice plot was sampled one before and 10 days after N fertiliser application. Five sub-samples of floodwater (100 ml each) were collected from each plot and mixed to make a single sample. All samples were brought to the laboratory and immediately analysed for NH_4-N and NO_3-N. Soil samples were collected at four main phenological stages of rice (tillering, panicle initiation, flowering and harvesting) from 0-20, 20-40, 40-70 and 70-100 cm soil depths and analysed for NH_4-N, NO_3-N, total-N, and organic carbon (OC). The second rice crop was transplanted at the end of wet season to dry season (1st April - 16th July 2008). The crop management and sampling procedures were similar to the first rice season. Similar crop management and sampling procedures were adopted for the second year of 2008-2009 experiment. Data were analysed using Genstat software (Version 9.2.0.153, VSN International Ltd, Oxford).

5.3 Results and discussion

5.3.1 NH_4-N dynamics in soil under various irrigation and N fertiliser treatments

The effects of irrigation and N fertiliser treatments on the NH_4-N concentration in soil during four rice growth seasons (2 wet seasons in 2007/2008 and 2008/2009 and 2 dry seasons in 2008 and 2009) at various soil layers and rice phenological stages are presented in Table 5.1. The seasons chronologically of 1st wet season of 2007 – 2008, 2nd dry season of 2008, 3rd wet season of 2008 – 2009 and 4th dry season of 2009 will be referred to as rice I, II, III and IV respectively.

Increased N fertiliser application rates had a significant effect on NH_4-N concentration in soil mainly in the top 20 cm depth in all four rice seasons and its influence mostly less prominent beyond the first soil layer in early stages of rice growth. Furthermore, significant influences of N fertiliser on NH_4-N concentration in soil were pronounced as development of rice growth progressed. Irrigation treatments had a much smaller influence than N fertiliser treatments on soil NH_4-N concentration in all rice seasons. In rice III and IV, irrigation treatment significantly influenced NH_4-N concentration in the top of 20 cm of soil mostly in the middle of growth periods (panicle initiation and flowering stages and harvesting stage in rice III). The interactive effect of irrigation and N fertiliser treatments on NH_4-N concentration in soil was observed on a rare occasion (only at flowering in the rice season III for 40-70 cm depth).

Figure 5.1 shows the variation of NH_4-N concentration at various soil depths and rice growth stages as affected by N fertiliser treatments during rice I and II. NH_4-N concentration in soil increased as N fertiliser application rates increased and accumulated mainly in the first 20 cm soil depth. The concentration of NH_4-N in soil was higher at tillering stage (33 days after transplanting, DAT) due to the application of first split of 20 % of total N fertiliser rate at 7 DAT and decreased at panicle initiation (53 DAT) although second split of 30% of total N fertiliser rate was applied at 34 DAT. At flowering stage (63 DAT), NH_4-N concentration in soil increased again due to the application third split of 50 % of total N fertiliser at 54 DAT and it decreased at harvesting stage. The decrease of soil NH_4-N concentration was probably due to uptake by the rice plants (Chapter IV, section 4.3.4) that increased as N fertiliser application rates increased.

Table 5.1 Summary of analysis of variance (ANOVA) for the effects of irrigation (I) and N fertiliser (F) treatments on NH_4-N concentration in soil at various soil depths and growth stages of rice over four seasons. Significance of treatment effects is denoted as '*' for $p \leq 0.001$; '**' as $p \leq 0.01$; '*' for $p \leq 0.05$ and 'NS' for not significant.**

Soil layer (cm)	Rice wet season (2007-2008)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	NS	***	NS	NS	***	NS	NS	***	NS	NS	***	NS
20-40	NS	NS	NS	NS	***	NS	NS	***	NS	NS	*	NS
40-70	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	**	NS
70-100	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	***	NS

Soil layer (cm)	Rice dry season (2008)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	NS	***	NS	NS	***	NS	NS	***	NS	NS	***	NS
20-40	NS	NS	NS	NS	*	NS	NS	***	NS	NS	***	NS
40-70	NS	NS	NS	NS	NS	NS	NS	***	NS	NS	***	NS
70-100	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	***	NS

Soil layer (cm)	Rice wet season (2008-2009)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	NS	***	NS	*	***	NS	*	***	NS	*	***	NS
20-40	NS	***	NS	NS	***	NS	NS	***	NS	NS	**	NS
40-70	NS	**	NS	NS	*	NS	NS	***	*	NS	***	NS
70-100	NS	NS	NS	NS	NS	NS	NS	**	NS	NS	***	NS

Soil layer (cm)	Rice dry season (2009)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	NS	***	NS	*	***	NS	*	***	NS	NS	***	NS
20-40	NS	***	NS	NS	***	NS	NS	***	NS	NS	***	NS
40-70	NS	NS	NS	NS	**	NS	NS	***	NS	NS	***	NS
70-100	NS	NS	NS	NS	*	NS	NS	**	NS	NS	**	NS

The increased N-uptake by rice crop with increases in N fertiliser application rates has also reported in a number of previous studies (Arth and Frenzel, 2000; George et al., 1993; Ta and Ohira, 1982) although NH_4-N can be lost via NH_3 volatilization and other gaseous form of N via nitrification and denitrification (Adhya et al., 1996; Smith and DeLaune, 1984). Keerthisingshe et al. (1985) reported that application of ammonium fertiliser clearly increased exchangeable and non exchangeable forms of soil NH_4^+ in field experiments conducted in three sites in major rice growing areas in the Philippines.

In the current experiment, N fertiliser application rates significantly increased NH_4-N concentration in deeper soil layers as rice growth progressed, indicating that the applied of N fertiliser was transported to lower soil layers. At panicle initiation stage, NH_4-N of soil significantly increased with 0-40 cm soil depth as N fertiliser increased but not beyond this zone. Furthermore, soon after flowering, N fertiliser treatments strongly increased the NH_4-N concentration throughout 0-70 cm soil depth. Any increase of NH_4-N concentration in soil within 20-70 cm soil depth was under N fertiliser rate at flowering stage. At harvest, significant increased NH_4-N concentration at all soil depths occurred under F2 but not for F0 and F1.

During rice II, the trend of soil NH_4-N concentration was similar to that for rice I. However, the influence of N fertiliser application rates on NH_4-N concentration in soil in rice II was greater than in rice I, while the amount of soil NH_4-N concentration in rice II (dry rice season of 2008) was lower than in rice I (rice wet season of 2007/2008). The high concentration of soil NH_4-N during wet season period could be due to mineralisation of soil organic matter and plant residues left in the field from previous planting. Similar results were also found by Phongpan and Mosier (2003) where NH_4-N accumulated in wet season was higher than in dry season in Central Plain region of Thailand. Low soil NH_4-N concentration during the dry season in lowland rice cropping systems in the Philippines was also recorded by George et al. (1994) and Tripathi et al. (1997).

The variation of soil NH_4-N concentration at various soil depths and rice growth stages as affected by N fertiliser treatments during rice wet season 2008/2009 (Rice III) and dry season 2009 (Rice IV) are presented in Fig. 5.2. The trend of soil NH_4-N concentration in rice III and IV seasons were almost similar to rice season in rice I and II. N fertiliser application rates increased NH_4-N concentration in soil in all rice growth periods in various soil layers. The interactive effect of irrigation and N fertiliser treatments on NH_4-N concentration in soil was not significantly different during rice growth periods in the second year of field experiment. However, NH_4-N concentration in soil was greater in the first year of rice seasons (2007-2008) than in the second year of rice seasons (2008-2009). In both years rice cropping cycles of 2007-2008 and 2008-2009 showed that NH_4-N concentration in soil was higher in the surface soil layer (0-20 cm) and less prominent beyond the soil surface layer. A similar result was found by Aulakh el at. (2000) where soil NH_4-N concentration was generally greatest in surface layer (0-15) and less effect below surface layer on a sandy loam soil in the Punjab of India. They also found that rapid distribution of applied N fertiliser to lower soil depths in irrigated porous soil was evident where the amount of NH_4-N differed significantly between 0 N and 120 kg N ha^{-1} fertiliser treatments.

The influence of irrigation treatments on NH_4-N concentration in soil at 0-20 cm soil depth in the second year of the rice season 2008-2009 at various phenological stages are presented in Fig. 5.3. Soil NH_4-N concentration was higher in CS than in ASNS from panicle initiation to harvesting stages in rice III and at panicle initiation and flowering stages in rice IV. This was probably due to the effects of non-submergence periods in the middle of rice growth that caused NH_4-N in soil to be transformed to NO_3-N via nitrification (Reddy and Patrick, 1986; Aulakh and Bijay-Singh, 1997).

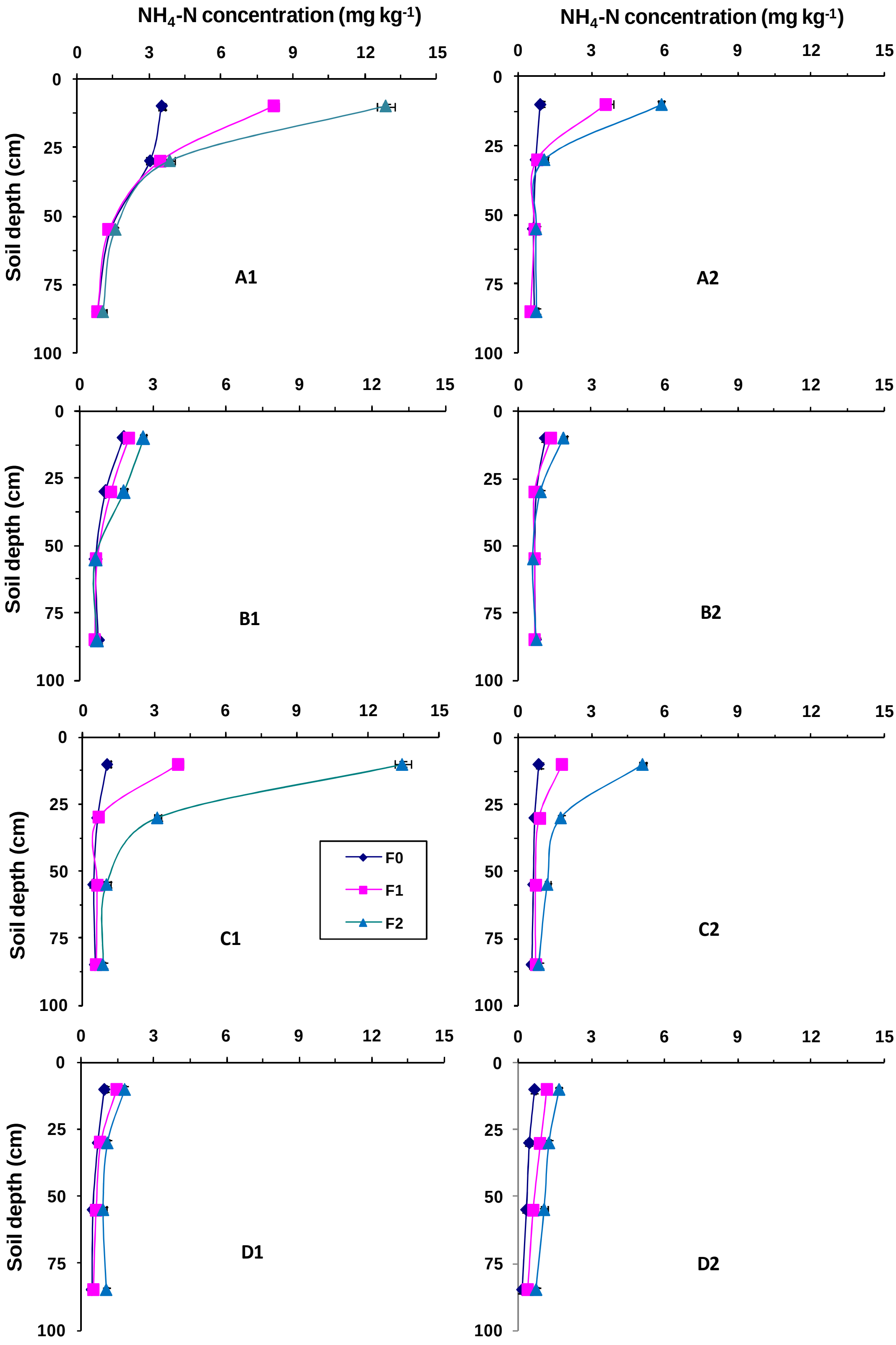

Figure 5.1 Influence of N fertiliser (F0 = 0 kg N ha^{-1}); F1 = 70 kg N ha^{-1} and F2 = 140 kg N ha^{-1}) on NH_4-N concentration in soil in various soil depths at tillering (A), panicle initiation (B), flowering (C) and harvesting (D) stages in rice wet season 2007/2008 (2).

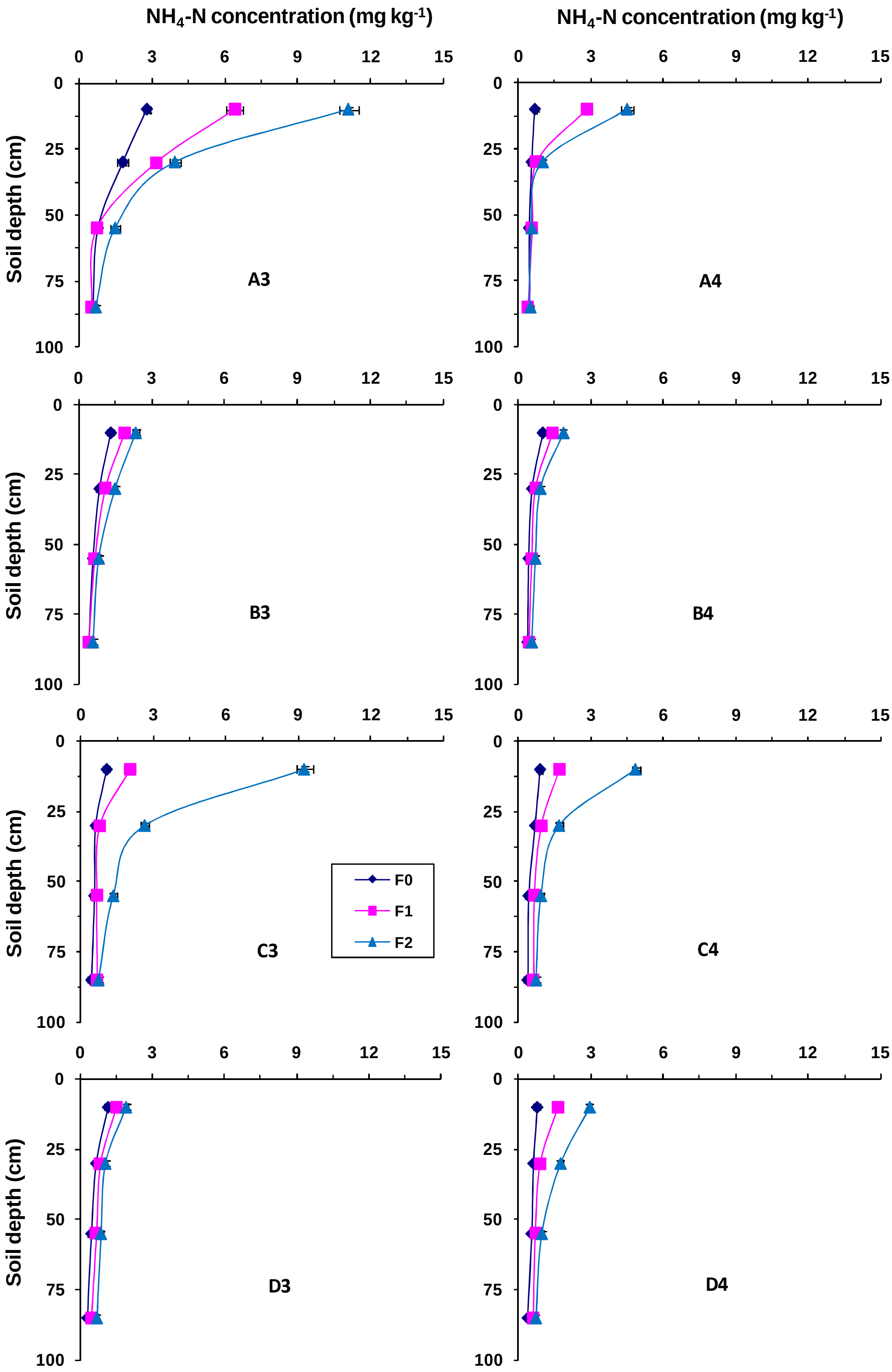

Figure 5.2 Influence of N fertiliser ((F0 = 0 kg N ha^{-1}); F1 = 70 kg N ha^{-1} and F2 = 140 kg N ha^{-1}) on NH_4-N concentration in soil in various soil depths at tillering (A), panicle initiation (B), flowering (C) and harvesting (D) stages in rice wet season 2008/2009 (4).

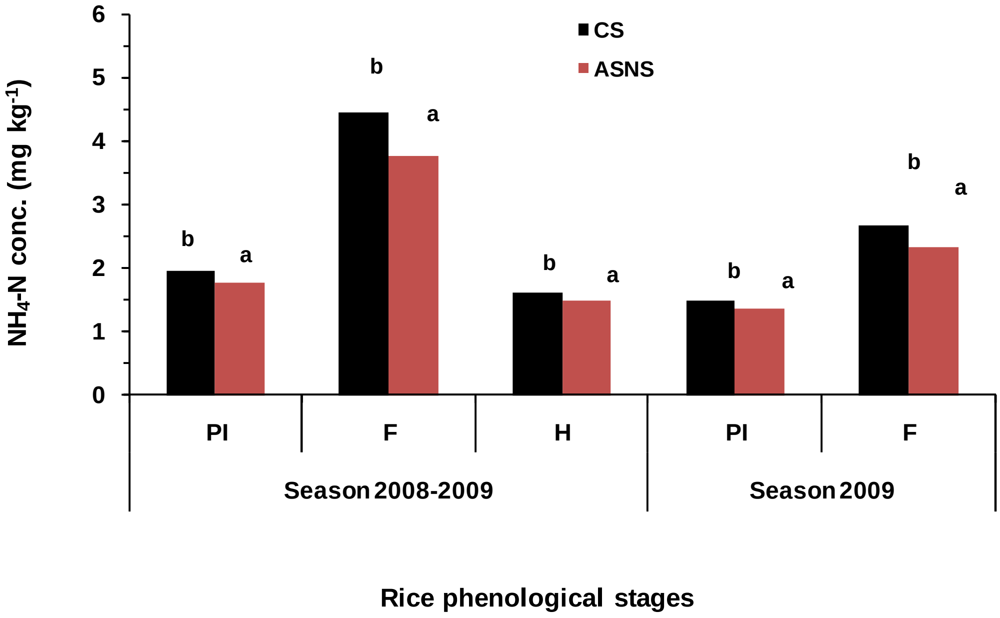

Figure 5.3 Influence of irrigation treatment (CS = continuously submerged and ASNS = alternately submerged and non-submerged) on NH_4-N concentration in soil at 0-20 cm soil depth at panicle initiation (PI), flowering (F) and harvesting (H) stages in rice reasons of 2008/2009 and 2009. For specific NH_4-N concentration in soil, similar letter(s) within the set of phenological stages (PI, F, H, PI and F) indicate that the difference between mean values are less than LSD. LSD values in each phenological stages were 0.049, 0.046, 0.036, 0.048 and 0.048 mg kg^{-1}, respectively.

5.3.2 NO_3-N dynamics in soil under various irrigation and N fertiliser treatments

The effects of irrigation and N fertiliser treatments on NO_3-N concentration in soil during four rice seasons (2 wet seasons of 2007/2008 and 2008/2009 and 2 dry seasons of 2008 and 2009) at various soil depth and phenological stages are presented in Table 5.2. NO_3-N concentration in soil was highly effected by N fertiliser application rates in most soil layers in all rice growing seasons. Irrigation treatment had no effect on NO_3-N concentration in soil in rice I, while in rice II, III and IV, irrigation treatment significantly influenced NO_3-N concentration in the top 20 cm soil depth mostly during the middle of growth periods (panicle initiation and flowering stages and only at harvesting stage in the rice III for 70-100 cm depth). The interactive effect of irrigation and N fertiliser treatments on NO_3-N concentration in soil was observed on rare occasion (only at tillering stage in the rice II season of rice for 20-40 cm depth).

Table 5.2 Summary of analysis of variance (ANOVA) for the effects of irrigation (I) and N fertiliser (F) treatments on NO_3-N of soil in various soil layers and growth stages of rice crop in various seasons. Significance of treatment effects is denoted as '*' for $p \leq 0.001$; '**' as $p \leq 0.01$; '*' for $p \leq 0.05$ and 'NS' for not significant.**

Soil layer (cm)	Rice wet season (2007/2008)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	NS	***	NS	NS	***	NS	NS	***	NS	NS	**	NS
20-40	NS	NS	NS	NS	***	NS	NS	***	NS	NS	*	NS
40-70	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	**	NS
70-100	NS	NS	NS	NS	NS	NS	NS	***	NS	NS	***	NS

Soil layer (cm)	Rice dry season (2008)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	NS	***	NS	*	***	NS	*	***	NS	NS	***	NS
20-40	NS	***	*	NS	**	NS	NS	***	NS	NS	**	NS
40-70	NS	NS	NS	NS	***	NS	NS	**	NS	NS	***	NS
70-100	NS	NS	NS	NS	**	NS	NS	***	NS	**	***	NS

Soil layer (cm)	Rice wet season (2008/2009)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	NS	***	NS	*	**	NS	*	***	NS	NS	***	NS
20-40	NS	***	NS	NS	***	NS	*	***	NS	NS	***	NS
40-70	NS	**	NS	NS	NS	NS	NS	**	NS	NS	***	NS
70-100	NS	***	NS	NS	***	NS	NS	***	NS	NS	***	NS

Soil layer (cm)	Rice dry season (2009)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	*	***	NS	*	***	NS	**	***	NS	NS	***	NS
20-40	NS	***	NS	*	***	NS	*	***	NS	NS	***	NS
40-70	NS	***	NS	NS	*	NS	NS	**	NS	NS	***	NS
70-100	NS	**	NS	NS	*	NS	NS	NS	NS	NS	***	NS

Figure 5.4 shows the variation of soil NO_3-N concentration at various soil depths and phenological stages of rice growth as affected by N fertiliser treatments during rice season of 2007/2008 and 2008 (rice I and II). NO_3-N concentration in soil significantly increased as N fertiliser increased at 0-20 cm soil depth in all phenological stages of all rice seasons although it values was lower as rice growth progressed. Increase in soil NO_3-N concentration at flowering stage was probably due to the application of N fertiliser 15 days before flowering stage.

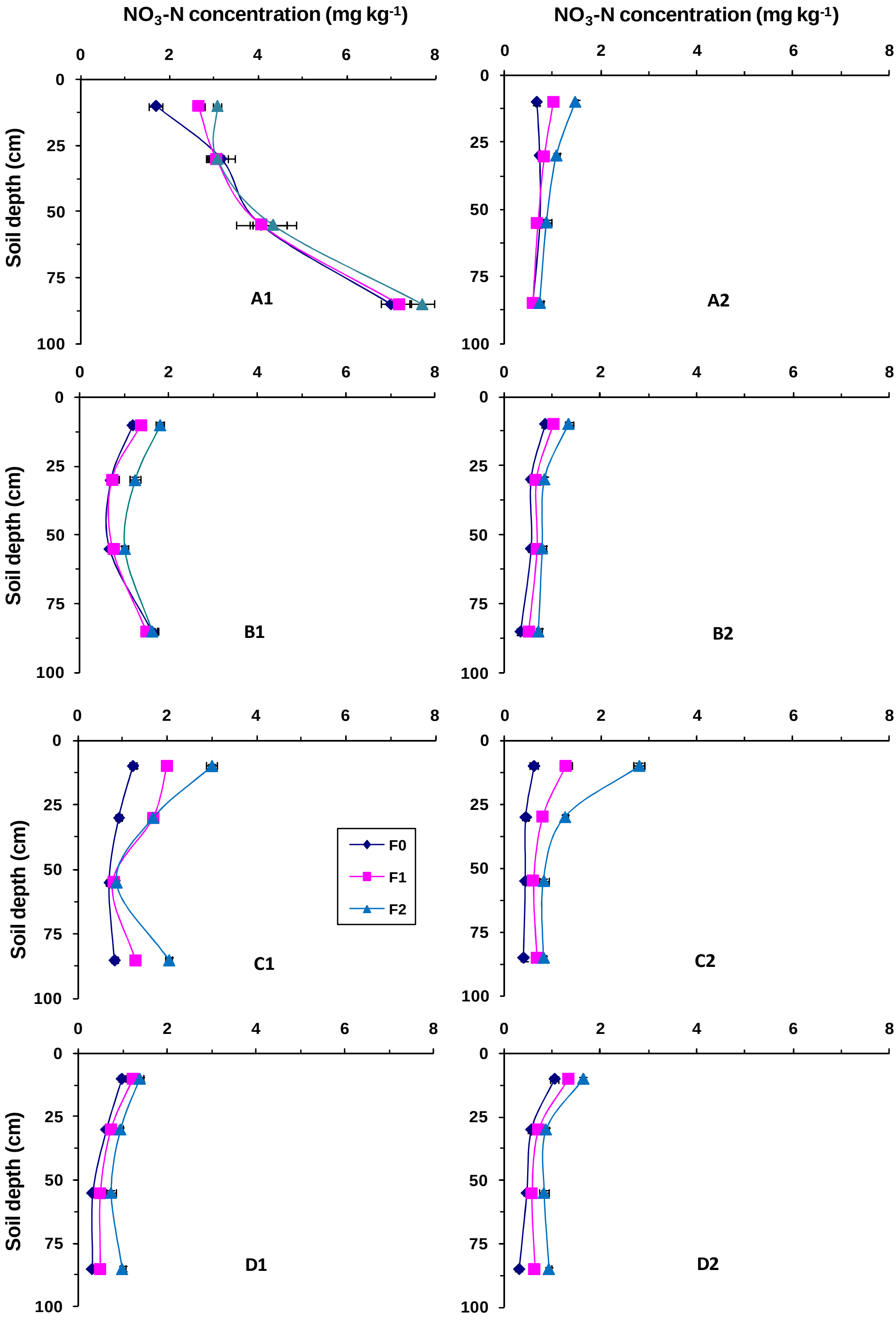

Figure 5.4 Influence of N fertiliser (F0 = 0 kg N ha^{-1}); F1 = 70 kg N ha^{-1} and F2 = 140 kg N ha^{-1}) on NO_3-N concentration in soil in various soil depths at tillering (A), panicle initiation (B), flowering (C) and harvesting (D) stages in rice season 2007/2008 (1) and 2008 (2)

The trend of soil NO_3-N concentration in 2008/2009 and 2009 seasons (rice III and IV) was similar to rice I and II (Fig. 5.5). However, NO_3-N concentration in soil was lower in the second year of experiment (2008-2009) than that in the first year of experiment (2007-2008). Regardless of N fertiliser and irrigation treatments, during the early stage of 2007/2008 and 2008/2009 rice growths, NO_3-N concentration in soil generally increased as soil depth increased. This was probably due to nitrate residues accumulated during dry to wet transition condition of soil where the experiment site was planted with peanut and soybean following second rice during dry season from July – November 2007. This also indicated that NO_3-N in soil was leached below root zone which cannot be taken up by plant. Accumulation of NO_3-N during dry to wet transition was prone to loss through denitrification and leached below root zone (George et al., 1993; Buresh et al., 1993; Ladha et al,. 1996). N losses through denitrification are well documented and reported (Bacon et al., 1986; George et al., 1994; Pande and Becker, 2003).

Variation of NO_3-N concentration in soil as affected by irrigation treatments in 0-20 cm soil depth in rice II, III and IV seasons at various phenological stages are presented in Fig. 5.6. Soil NO_3-N concentration was higher in ASNS than that in CS at panicle initiation and flowering stages in rice II, III and IV seasons. At the same time, soil NH_4-N concentration was higher in CS than that in ASNS mainly in the middle of rice growth periods in rice III and IV (section 5.3.1). This may be due to the effect of drainage condition during nonsubmergence periods which surface soil become aerobic condition.

When surface soil was exposed to aerobic condition, nitrification started to take place which reduced the availability of NH_4-N (Reddy and Patrick, 1986; Aulakh and Bijay-Singh, 1997). A large number of nitrifying organisms have been shown to occur in the surface layers of flood soils although nitrifying activity in flooded soils may be substantially lower than in unflooded soils (Engler and Patrick, 1974). Furthermore, most of NH_4-N concentration was in surface soil which may accelerate nitrification. Lower NH_4-N concentration and higher NO_3-N concentration in soil in ASNS than in CS could explain the occurrence of nitrification during nonsubmergence period in surface soil.

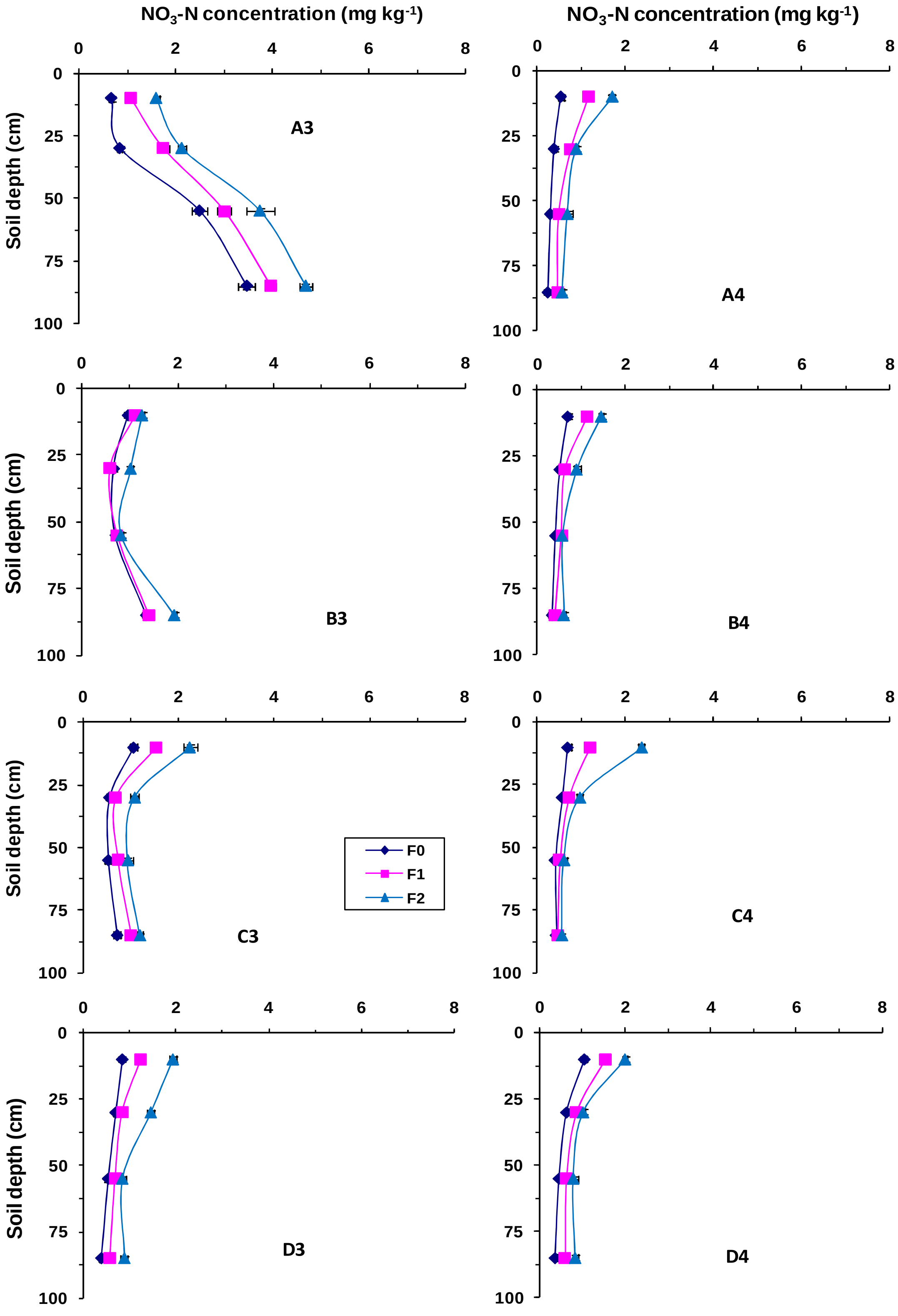

Figure 5.5 Influence of N fertiliser (F0 = 0 kg N ha^{-1}); F1 = 70 kg N ha^{-1} and F2 = 140 kg N ha^{-1}) on NO$_3$-N concentration in soil in various soil depths at tillering (A), panicle initiation (B), flowering (C) and harvesting (D) stages in rice season 2008/2009 (3) and 2009 (4).

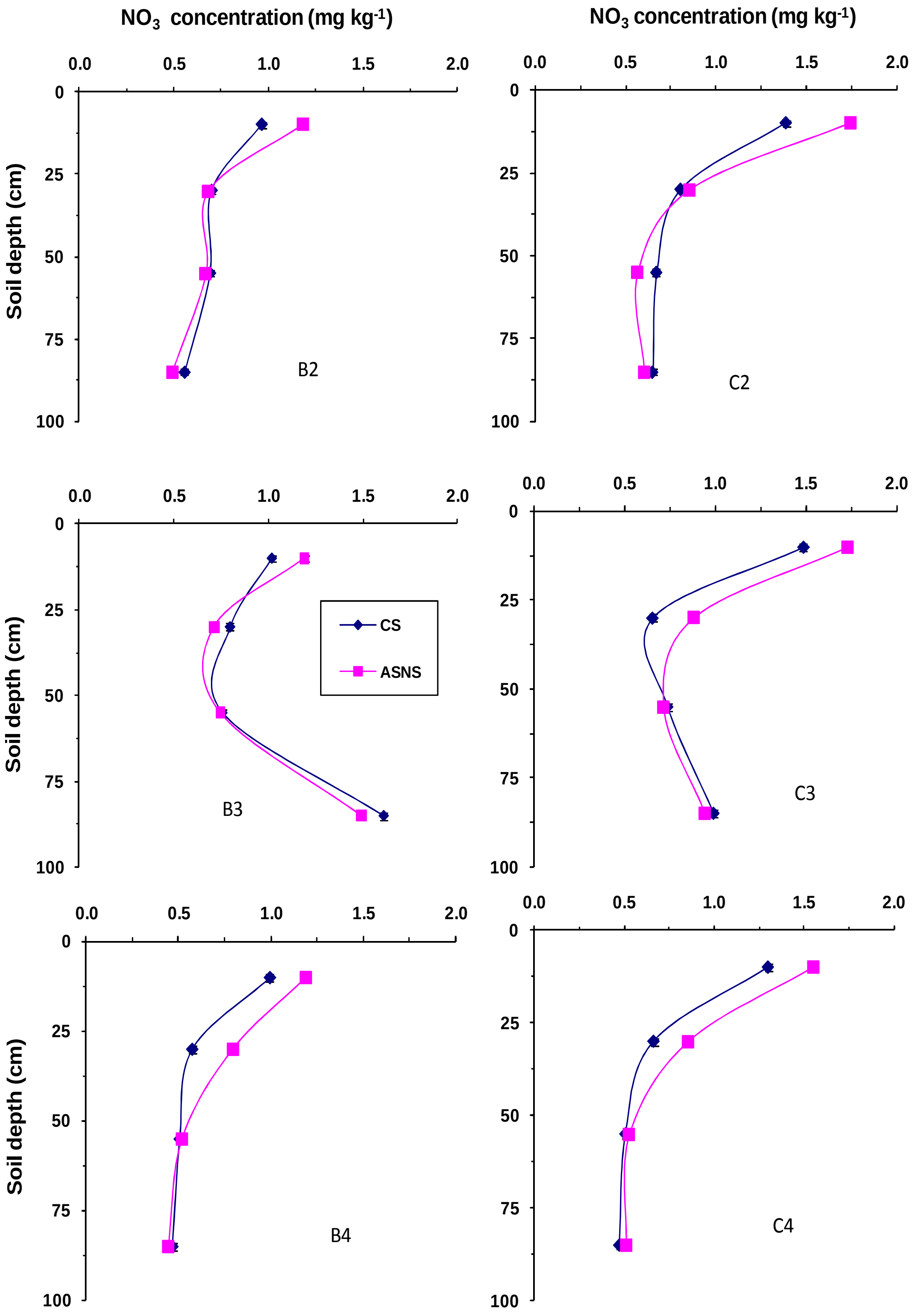

Figure 5. 6 Influence of irrigation treatment (CS = continuously submerged and ASNS = alternately submerged and non-submerged) on NO_3-N concentration in soil in various soil depths at panicle initiation (B) and flowering (C) stages of rice reason 2008 (2), 2008/2009 (3) and 2009 (4).

Tabbal et al. (1992) showed that the level of ammonium in soil was lower, and that of nitrate was higher, in ASNS than in flooded rice fields. Upon subsequent flooding, nitrate could be leached or undergo denitrification losses and N losses may be higher in ASNS than in conventional flooding. However, Belder et al. (2004) found similar N uptake and (fertilizer-N) recoveries under flooded and ASNS conditions, in experiments where shallow groundwater tables kept the soil relatively wet during non-submerged periods. There was no significant affect of irrigation at the harvesting stage in all rice seasons, which may be due to the fact that all plots were drained 10 days before harvest which may be soil exposed to an aerobic condition. However, the amounts of NO_3-N concentration in soil at 70-100 cm soil tended to higher in CS than in ASNS. This indicated that ASNS water regime may also reduce nitrogen contamination to the groundwater.

5.3.3 Total-N dynamics in soil under various irrigation and N fertiliser treatments

Table 5.3 shows the effects of irrigation and N fertiliser treatments on total-N of soil during four rice growth seasons (2 wet seasons of 2007/2008 and 2008/2009 and 2 dry seasons of 2008 and 2009) at various soil layers and phenological stages. N fertiliser significantly influenced total-N soil as rice growth progressed mostly at 0-40 cm soil depth and this effect was more pronounced as rice cycling season progressed. There was no interactive effect of irrigation and N fertiliser treatment on soil total-N during rice growth in all growing seasons. Total-N of soil was not influenced by irrigation treatment in all rice seasons in the first year (2007-2008) and in rice season 2008/2009 of field experiment except at harvesting stage. However, irrigation treatments had significant affect on total-N concentration in soil in season 2009 at 0-20 cm soil depth except at tillering stage.

Figure 5.7 shows the distribution of soil total-N content at various soil depths and phenological stages of rice growth as affected by N fertiliser during rice season of 2007/2008 and 2008. Total-N concentration in soil increased as N fertiliser increased during rice growth periods. Total-N concentration in soil was mostly accumulated in soil surface (0-20 cm depth) and sharply decreased as soil depth increased. A similar trend of total-N concentration in soil was also observed at 2008/2009 and 2009 seasons (Fig. 5.8). Soil total-N in 2008/2009 rice wet season was higher than that in 2007/2008 rice wet season, probably as results of mineralisation of soil organic matter or residues during legumes planting prior to rice crop. Soybean and peanut crops were planted after harvesting the rice dry season of 2008 and 2009. In addition, rice straw was returned on each plot as mulch during soybean and peanut growth periods.

The irrigation treatment had no effect on total-N concentration in soil during the first year of field experiment (2007-2008). As rice growth cycles progressed however, total-N concentration in soil was significantly higher in CS than that in ASNS (Fig. 5.9). This was probably due to frequent wetting and drying cycles in ASNS treatment that accelerate decomposition of organic carbon resulting in N mineralisation. Drying and rewetting of soils is well known to enhance carbon and nitrogen mineralisation (van Gestel et al., 1993). Mikha et al. (2005) reported that repeated drying and wetting cycles significantly reduced cumulative N mineralisation compared with constant water content. The reduction in cumulative mineralized C resulting from drying and wetting compared with constant water content treatments increased as the drying and wetting treatments were subjected to additional cycles. According to Franzluebbers et al. (1994), repeated drying and wetting cycles could cause a reduction in net N mineralisation, either because of chemical reactions during the drying period, which reduce the amount of available N or reduce the active microbial biomass, or because of a change in species composition, in which instance more N could be retained in the microbial cells. Accumulation of N in a less-available portion of dead microbial biomass after each rewetting event could further reduce net N mineralisation (Franzluebbers et al., 1994). Furthermore, total-N concentration in soil decreased as rice growth progressed. This trend was support the previous study by Kyaw et al. (2005) in FM Hommachi, FS Centre, Japan that the inorganic N contents of the soil surface (0-15 cm depth) after harvesting in two years experiment were about half of those before cultivation.

Table 5.3 Summary of analysis of variance (ANOVA) for irrigation (I) and N fertiliser (F) treatments on total-N of soil in various soil layers and growth stages of rice crop at various seasons. Significance of treatment effects is denoted as '*' for p ≤0.001; '**' as p ≤ 0.01; '*' for p ≤ 0.05 and 'NS' for not significant.**

Soil layer (cm)	Rice wet season (2007/2008)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	*	NS
20-40	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	***	NS
40-70	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
70-100	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Soil layer (cm)	Rice dry season (2008)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	NS	***	NS	NS	**	NS	NS	***	NS	NS	***	NS
20-40	NS	NS	NS	NS	*	NS	NS	***	NS	NS	***	NS
40-70	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
70-100	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Soil layer (cm)	Rice wet season (2008/2009)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	NS	*	NS	NS	***	NS	NS	***	NS	**	***	NS
20-40	NS	NS	NS	NS	**	NS	NS	**	NS	NS	NS	NS
40-70	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
70-100	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Soil layer (cm)	Rice dry season (2009)											
	Tillering			Panicle initiation			Flowering			Harvesting		
	I	F	I×F	I	F	I×F	I	F	I×F	I	F	I×F
0-20	NS	***	NS	*	***	NS	*	***	NS	*	***	NS
20-40	NS	NS	NS	NS	NS	NS	NS	**	NS	NS	*	NS
40-70	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
70-100	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

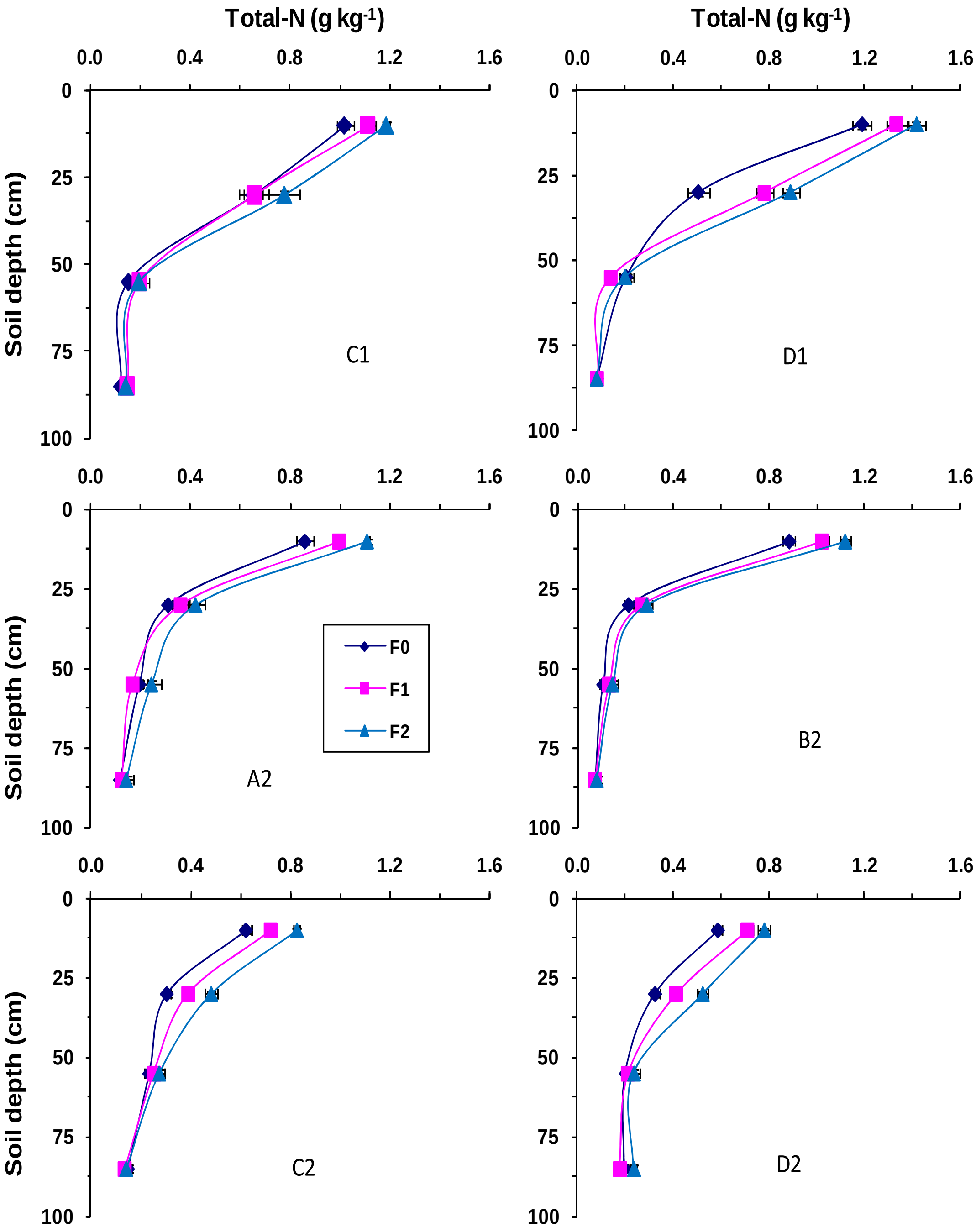

Figure 5.7 Influence of N fertiliser (F0 = 0 kg N ha^{-1}); F1 = 70 kg N ha^{-1} and F2 = 140 kg N ha^{-1}) on total-N concentration in various soil depths at tillering (A), panicle initiation (B), flowering (C) and harvesting (D) stages in rice season 2007/2008 (1) and 2008 (2).

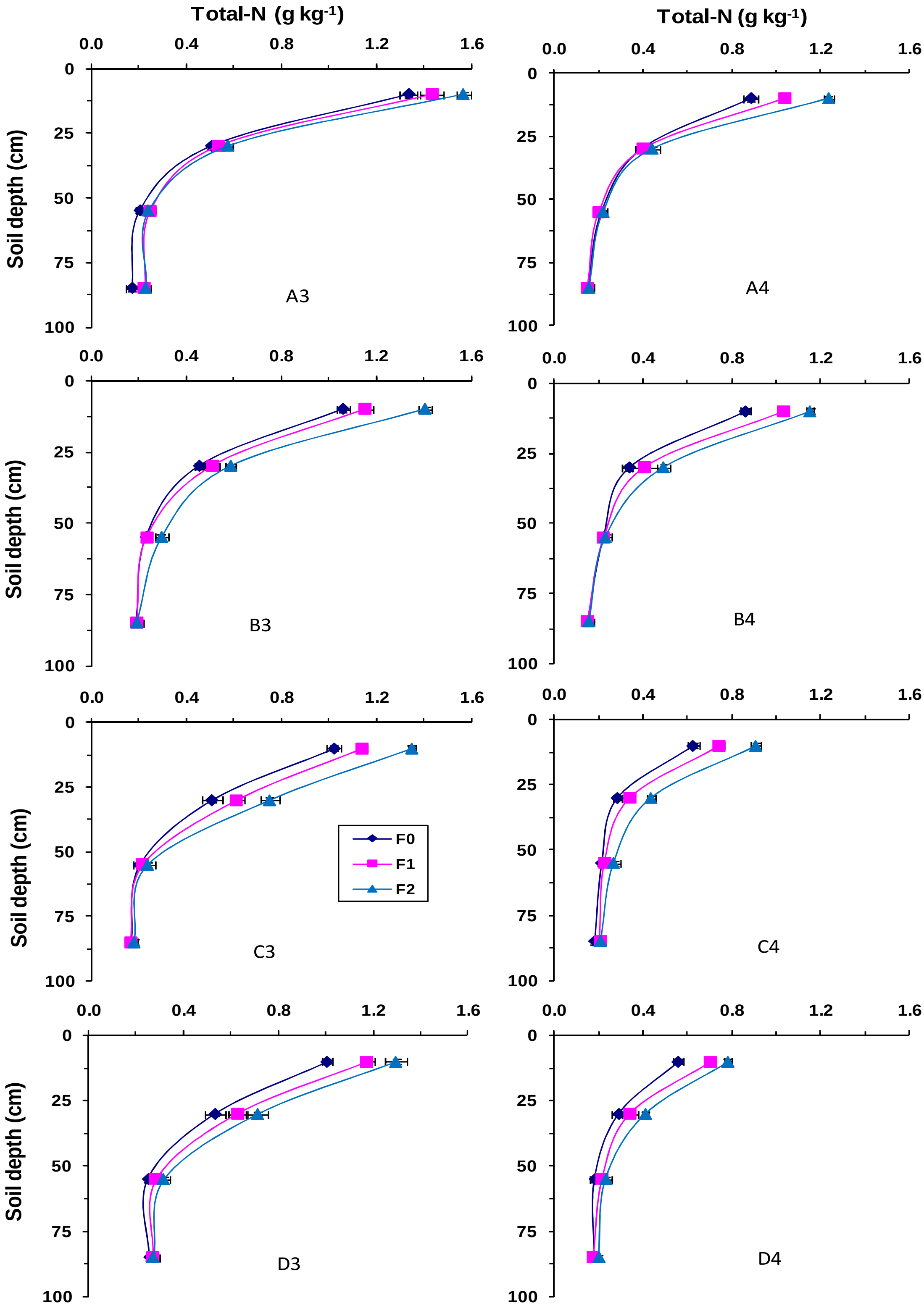

Figure 5.8 Influence of N fertiliser (F0 = 0 kg N ha^{-1}); F1 = 70 kg N ha^{-1} and F2 = 140 kg N ha^{-1}) on total-N concentration in various soil depths at tillering (A), panicle initiation (B), flowering (C) and harvesting (D) stages of rice season 2008/2009 (3) and 2009 (4).

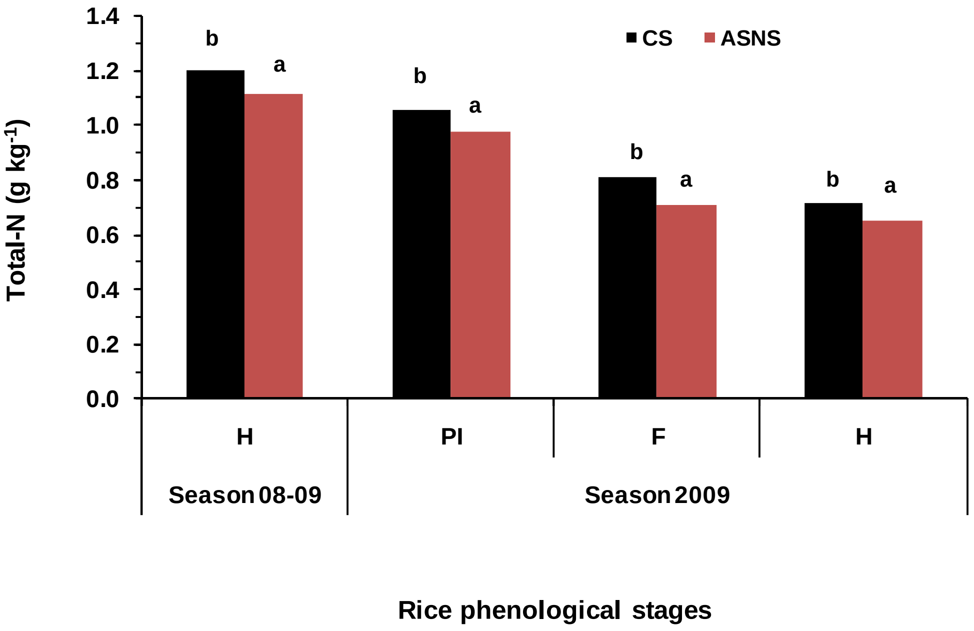

Figure 5.9 Influence of irrigation treatments (CS = continuously submerged and ASNS = alternately submerged and non-submerged) on total-N concentration in soil at 0-20 cm soil depth at panicle initiation (PI), flowering (F) and harvesting (H) stages during rice reasons of 2008/2009 and 2009. For specific total-N, similar letter(s) within the set of four phenological stages (H, PI, F and H) indicate that the differences between mean values are less than LSD. LSD values in each phenological stages were 0.005, 0.031, 0.045, 0.047 g kg^{-1}, respectively.

5.3.4 Organic carbon dynamics in soil under various irrigation and N fertiliser treatments

In all seasons, the effect of N fertiliser application rates and irrigation treatments on soil organic carbon was rarely observed during rice growth periods in 2007-2008 and 2008/2009. Significance effect of irrigation treatments on OC concentration was only observed at harvesting in the rice III season and at flowering and harvesting in the rice IV season at the 0-20 cm depth.

Irrigation treatment had no effect on OC concentration in soil during the first year of field experiment (2007-2008). However, as rice growth cycles progressed, OC concentration in soil was significantly higher in CS than that in ASNS (Fig. 5.10). This was probably due to frequent wetting and drying cycles in ASNS treatment that accelerate decomposition of organic carbon as discussed in the section 5.3.3.

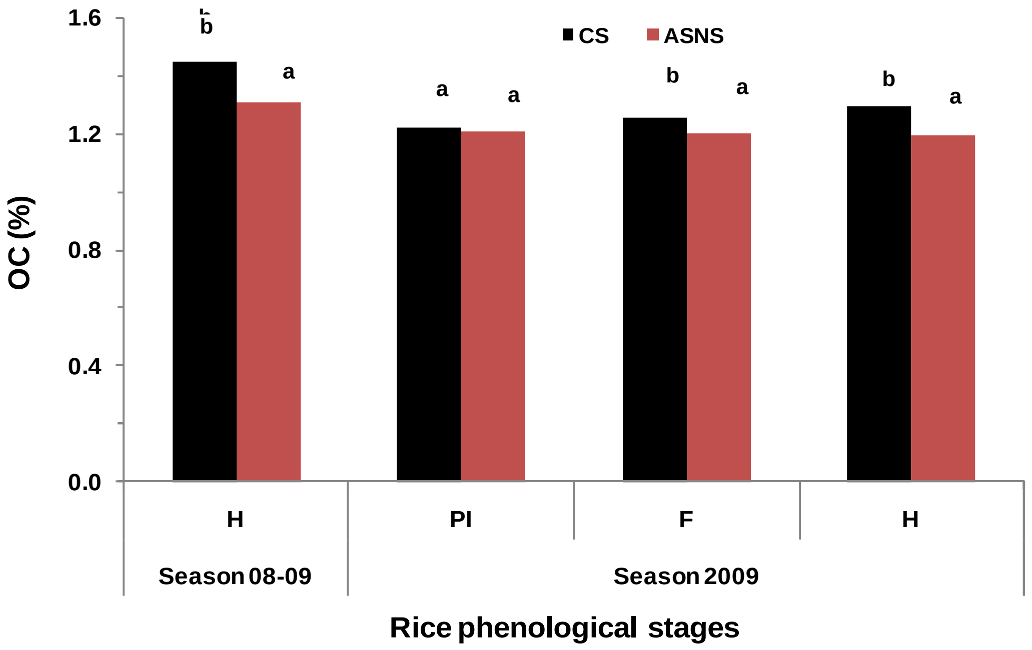

Figure 5.10 Effects of irrigation treatments (CS = continuously submerged and ASNS = alternately submerged and non-submerged) on organic carbon (OC) concentration in soil at 0-20 cm soil depth at panicle initiation (PI), flowering (F) and harvesting (H) stages in rice reasons of 2008/2009 and 2009. For specific total-N, similar letter(s) within the set of four phenological stages (H, PI, F and H) indicate that the differences between mean values are less than LSD. LSD values in each phenological stages were 0.042, 0.049, 0.045 and 0.047 g kg^{-1}, respectively.

5.3.5 NH_4-N and NO_3-N in floodwater during rice growth periods

The dynamics of NH_4-N and NO_3-N in floodwater at various irrigation and N fertiliser treatments in four rice growth seasons (2 wet and dry seasons in 2007/2008 and 2008/2009 and in 2008 and 2009 respectively) are presented in Fig. 5.11 and 5.12. Floodwater samples were collected for one day before and for 10 days after N fertiliser application. NH_4-N and NO_3-N were not significantly affected by irrigation treatment, but their concentrations in floodwater increased soon after N fertiliser applied, indicating that urea (N fertiliser) was hydrolysed rapidly (Ma et al., 1995).. NH_4-N from hydrolysed urea became readily available throughout the root zone to be taken up by plant. Xu et al. (2000) reported that NH_4-N concentration in floodwater increased during the first 6 days after urea fertiliser was applied. The results in this experiment have shown that the increases in NH_4-N concentration of floodwater varied depending on the amount and times of N fertiliser application. Figure 5.11 shows that for F1 treatment the increase inNH$_4$-N concentration in floodwater lasted for 5, 6, 7 days after the first, second and third N fertiliser application, respectively. In F2 treatment, the increase in NH_4-N concentration lasted for 6, 7 and 9 days after the first, second and third N fertiliser application respectively.

NO_3-N concentration in floodwater increased soon after N fertiliser was applied and decreased with time (Fig. 5.12). However, NH_4-N concentration in floodwater was higher than NO_3-N concentration during observation. The higher concentration NH_4-N than NO_3-N was probably due to water flooding condition. Applied urea may transform to NH_4-N by hydrolysis processes (Chowdary et al., 2004) and small portion of NH_4-N tends to change to NO_3-N because the nitrification rate is slow under flooding condition (Cho and Han, 2002). It has been well understood that nitrification of NH_4-N is slower in anaerobic condition than in aerobic because microorganisms involved in nitrification prefer in aerobic to anaerobic conditions (Choi et al., 2003). Furthermore, retardation of vertical movement of NH_4^+ due to adsorption of negative charged of soil particles might also contribute to the higher concentration of NH_4^+ in the floodwater. Yoon et al. (2006) reported that inorganic N in rice floodwater consists of 65% NH_4-N and 30% NO_3-N on silty loam soil (Fluventic Haplaquepts) at Maryung-myun, Chonbuk province of Korea. In this study, the inorganic N in rice floodwater during whole seasons consisted of 63% NH_4-N and 37% NO_3-N. The proportion of NO_3-N in this study was higher than reported by Yoon et al. (2006) probably due to soil type used in this study and rice culture managements.

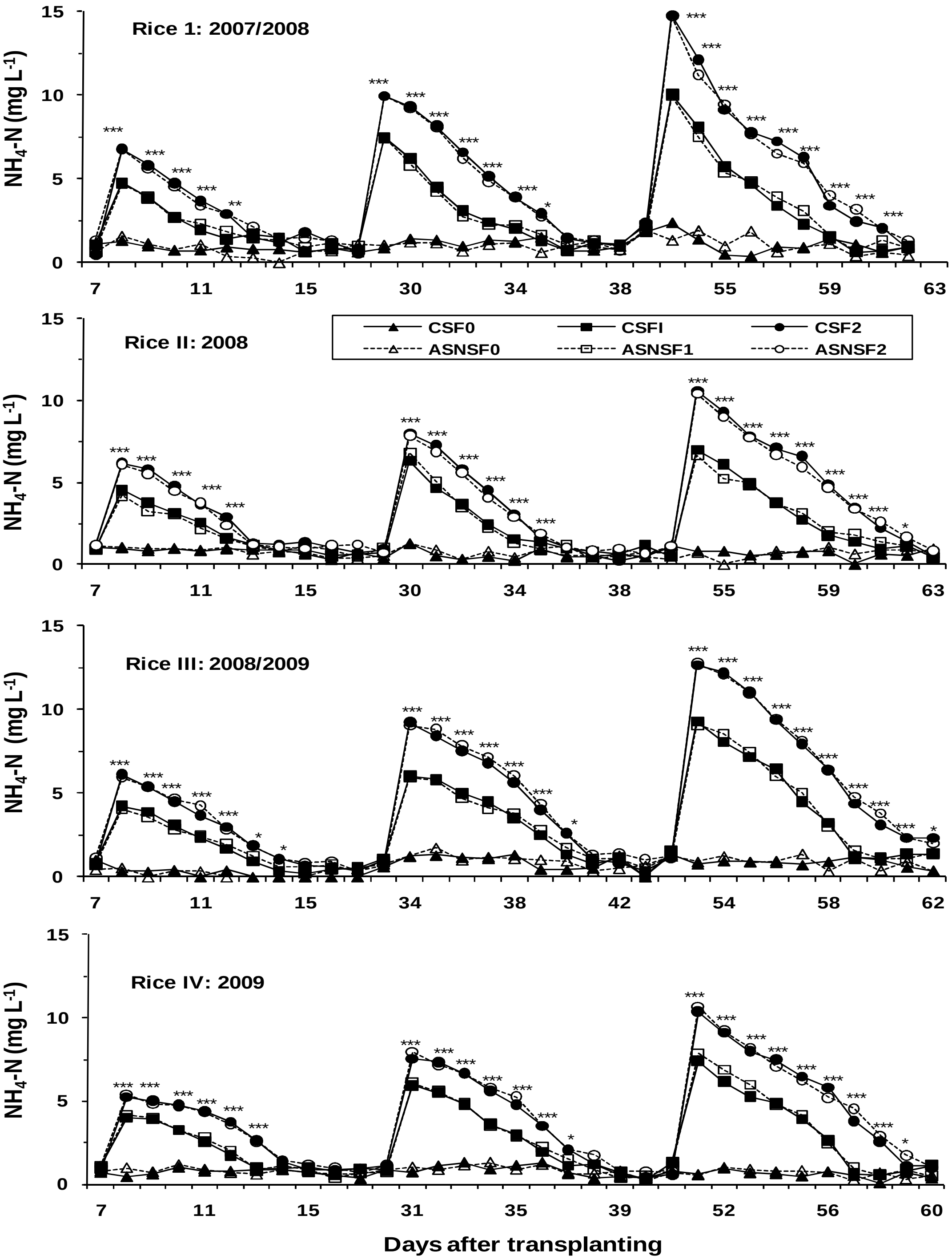

Figure 5.11 NH_4-N dynamics in floodwater during rice growth as influenced by N fertiliser and irrigation treatments during four rice growth periods in 2007/2008, 2008, 2008/2009 and 2009 seasons. For N fertiliser treatments, significance of treatments is denoted as '*' for $p \leq 0.001$; '**' for $p \leq 0.01$ and '*' for $p \leq 0.05$.**

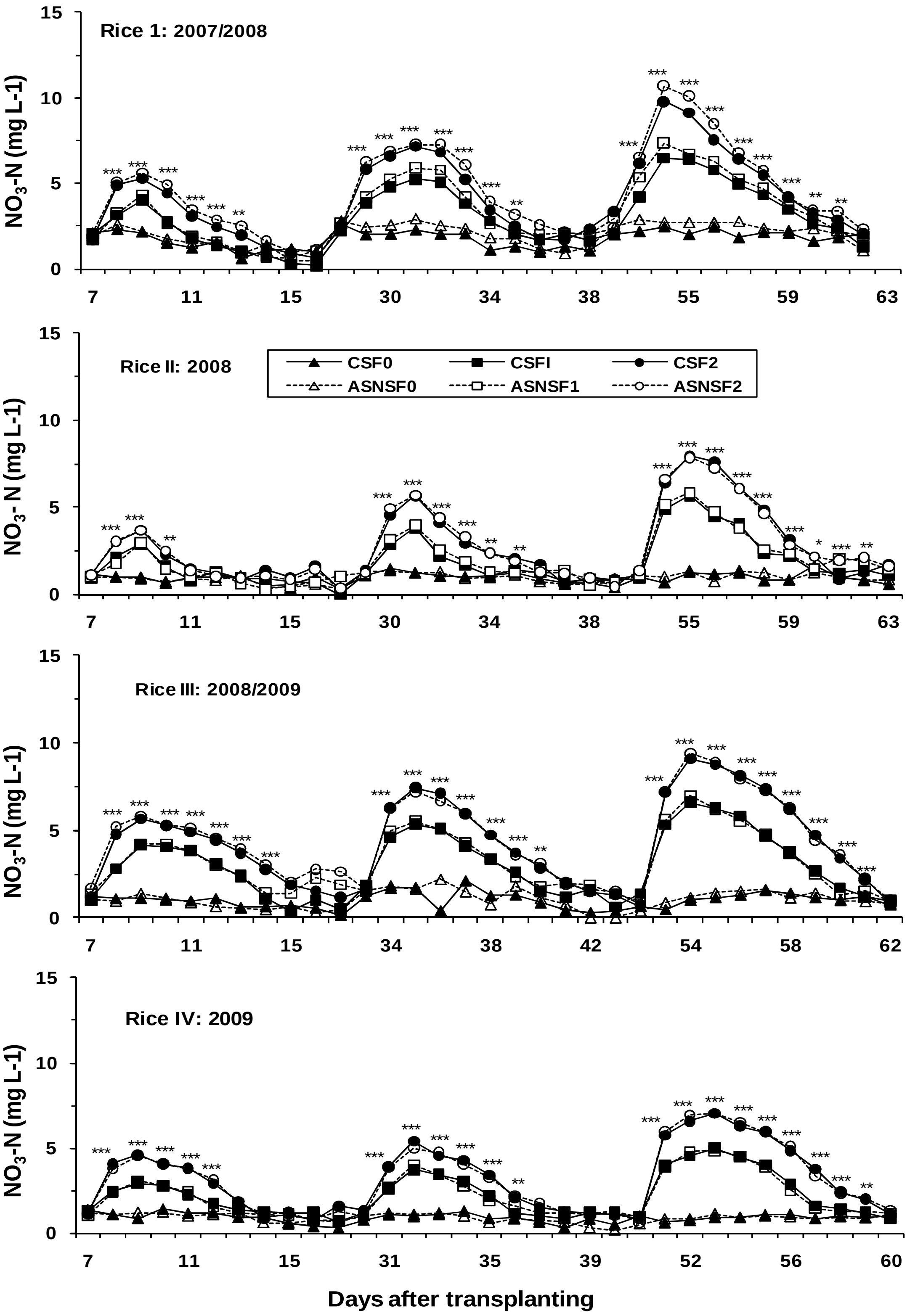

Figure 5.12 NO$_3$-N dynamics in floodwater during rice growth as influenced by N fertiliser and irrigation treatments during four rice growth periods in 2007/2008, 2008, 2008/2009 and 2009 seasons. For N fertiliser treatments, significance of treatments is denoted as '*' for $p \leq 0.001$; '**' for $p \leq 0.01$ and '*' for $p \leq 0.05$.**

5.4 Concluding remarks

The results of two years field study on the effects of irrigation and N fertiliser treatments on the dynamics of nitrogen in rice-based cropping systems showed that NH_4-N and NO_3-N concentration in soil increased as N fertiliser application rates increased during the rice growth periods. Soil NH_4-N concentration was not affected by irrigation in early rice season but its effect was more pronounced as season progressed especially during panicle initiation and flowering. During this period, NH_4-N concentration in soil was higher in CS than in ASNS mostly in the 0-20 cm soil depth whereas NO_3-N concentration in soil was lower. This suggests that nitrification occurred during nonsubmergence periods. Total-N and organic carbon of soil was not influenced by irrigation treatments in the first year (2007-2008) of the experiment but its effects were pronounced in the second year (2008-2009) of the experiment. Total-N and organic carbon of soil was higher in CS than that in ASNS treatments at 0-20 cm soil depth, indicating that frequent drying and rewetting of soils subsequently enhanced carbon and nitrogen mineralisation. NH_4-N concentration of floodwater increased soon after N fertiliser was applied which suggests that urea (N fertiliser) was hydrolysed rapidly and some which may have transformed to NO_3-N through nitrification, although NH_4-N concentration in floodwater was higher than the NO_3-N concentration during the observation.

CHAPTER VI

Growth and yield of legumes and nitrogen dynamics following rice in tropical lowland rice-based cropping system

6.1 Introduction

Legumes are important opportunity crops which are usually planted during the dry season (July to October) after consecutive seasons of irrigated rice in the tropical lowland rice-based cropping systems.. Since rice is grown in anaerobic conditions for most part of its growth, aerobic conditions are essential to grow legumes in most tropical lowland rice-rice-legume crop sequence in eastern Indonesia.Legume crops such as soybean (*Glycine max* (L.) Mer) and peanut (A*rachis hypogaea* L.) are capable of biological nitrogen fixation (BNF) which reduce the need for N fertiliser. Although soybean and peanut can derive N through BNF, it may not fully meet the N-requirement of legumes throughout the season producing variable results with N fertiliser application. Many studies have shown an increase in yield and associated dry matter accumulation as a result of N application (Touchton and Rickerl, 1986; Afza et al., 1987; Wood et al., 1993; Lanier et al., 2005), while others have shown little or no response (Deibert et al., 1979; Schmitt et al., 2001; Barker and Sawyer, 2005) or even reduced yield and dry matter production (Peterson and Varvel, 1989). Other studies have also shown that application of N to legumes may reduce nodule formation (Chen et al., 1992; Starling et al., 1998; Daimon et al., 1999; Taylor et al., 2005; Ray et al., 2006; Basu et al., 2008). Reddy et al. (1981) suggested that variable response of the legumes to N fertiliser could be due to the differences in edaphic, environmental conditions and management decisions made during cropping. The performance of legumes in relation to N dynamics during the dry season in rice-based cropping systems of eastern Indonesia has not received much attention. As the rice-rice-legume cropping systems are important in maintaining soil-nitrogen balance which has important implication towards economic, environmental and biophysical sustainability of the system, further research is essential.

Understanding of N dynamics, especially the dynamics of NO_3-N during dry legume season under rice-rice-legume crop sequence is important not only to gain insight NO_3-N into potential loss into surface and ground water, but also for retention of N on land for its productive use. In upland crops fields, native and most applied forms of N may be readily nitrified so that NO_3 is the dominant form of N in the soil mineral fraction (Li et al., 2009). During an irrigation or rainfall event, this form of N may be lost primarily via leaching and to some extent via denitrification (Ponnamperuma, 1985; Buresh et al., 1989; George et al., 1993). Urea or ammonium-based fertilisers placed on the surface of coarse soils may be more prone to losses via ammonia volatilisation than in fine-textured soils. Monitoring concentrations and uptake of N is helpful for the understanding of plant and soil N status and in devising N-fertilizer strategies for both individual crops and a cropping system (Li et al., 2009). Data on N dynamics under legume crops in dry season of rice-rice-legume crops sequence are necessary to advice growers/farmers to conserve and effectively use soil N in lowland rice-based cropping systems.

The objectives of this study were: (i) to measure changes in soil N during legume crops period in the dry season; (ii) to evaluate response of legumes after the second rice crop is harvested in the dry season to N fertiliser.

6.2 Materials and methods

Full details of materials and methods related to this study are given in Chapter 3. In brief, peanut and soybean (Indonesia national varieties of ‘garuda’ and ‘wilis’, respectively) were immediately planted after the dry seasons of rice crop were harvested over 2 cropping seasons during July to November in 2008 and 2009. The experiment was based on a split-plot design with peanut and soybean as main plots and three rates of N-fertilisation (referred to as F0, F1 and F2 treatments to indicate 0, 12 and 24 kg N ha^{-1}, respectively) as subplots within each main plot in three blocks. Plant samples were collected at three key growth stages at vegetative, reproductive and harvesting to determine crop biomass, leaf area, total-N of crops and number and weight of nodules. Soil was sampled at the same time as crops sampling. Collection and measurement procedures were similar to the soil sampling for the rice crop. Soybean and peanut were harvested at physiological maturity and expressed at 11% moisture content. A 3 m x 2 m and 4 m x 2 m area within each plot for soybean and peanut respectively was used to sample grain yield and estimated in kg ha^{-1}. In the 2009 legume crops season, additional crop samples at 10 day intervals were collected to estimate biomass and number and weight of nodules. Data were analysed for Analysis of variance (ANOVA) using Genstat software (Version 9.2.0.153, VSN International Ltd, Oxford) and least significant difference (LSD) was calculated to explain the difference if one or more treatments had a significant effect on measured parameters.

6.3 Result and discussion

6.3.1 Dynamics of organic carbon and nitrogen under legumes and N fertiliser treatments

The effects of N fertiliser treatments and the types of legume crops planted following the harvesting of the second rice crop on nitrogen and organic carbon dynamics during 2008 and 2009 seasons are presented in Table 6.1The concentration of ammonium-N (NH_4-N) and nitrate-N (NO_3-N) in soil varied during the growth period of each legume depending on the type of crop and N fertiliser treatments. The concentration of NH_4-N and NO_3-N also varied with soil depth as a result of these treatments. The type of legume crops had little significant effects on NH_4-N and NO_3-N concentrations at various soil depths in both years. The effects of N fertiliser treatments were more pronounced than the type of legume with same interaction between the two factors.

Organic carbon concentration in soil at various depth and growth stages were not significantly affected by types of legume and N fertiliser treatments during both 2008 and 2009 cropping seasons. Total-N concentration in soil was not significantly affected by irrigation treatment, while N treatment had only small effect on total-N in soil within the top 40 cm soil depth at the harvesting of legume in 2009. Total-N and carbon content in soil may take several years to change (Wood et al., 1990; Curtin et al., 2000) as it is dependent on various soil, crops and climatic factors. Studies conducted in eastern Canada have shown that initial increase in soil organic carbon may vary within the first 12 years of continuous corn production (Liang et al., 1998). Organic carbon levels on a silt loam cropped with wheat in Saskatchewan, Canada, were thought to have reached a steady state after 10 years of cropping under no-tillage management (Curtin et al., 2000). Fortune at al. (2008) reported that nitrogen fertilizer treatments had no significant effects on total soil N or soil organic carbon at any depth at the Kentucky Agricultural Experimental Station in Lexington. Due to the inconspicuous effect of legume and N fertiliser treatments on total-N and organic carbon, these have been omitted from the summary of ANOVA in the Table 6.1

Figure 6.1 illustrates the dynamics of NH_4-N concentration at various soil depths as affected by N fertiliser and legume type treatments during 2008 and 2009 season following the harvest of the second rice crop. These types of legume are preferred by farmers in managing lowland rice-based cropping systems for more than 30 years in the region. As shown in Fig 6.1, NH_4-N concentration varied mostly due to N fertiliser application rates increase from F0 to F2. The concentration of NH_4-N was generally the highest in the surface soil layers (0-20 cm) and that declined with depth. Concentration of NH_4-N at all soil depths significantly increased with increase in N fertiliser application rates, although these differences were relative small at below 75 cm depth. Since the applied N fertiliser rapidly converts to NH_4-N components, high concentration of NH_4-N is imparted within the upper soil layers at least for some periods before it is converted into NO_3-N. Similar trends for NH_4-N concentration in soil have been previously observed by Aulakh et al. (2000) in rice-wheat crop sequence.

Spatial and temporal distribution of NO_3-N in soil for 2008 and 2009 seasons is shown in Fig. 6.2. Concentration of NO_3-N in soil varied with N fertiliser application rates and soil depth. The distribution of NO_3-N also peaked in the top 25 cm soil depth and declined with depth and decreased with N fertiliser application rates on order of $F0<F1<F2$ except for the vegetative stage in 2008 (A1). The concentration of NO_3-N in soil was 2-3 times higher than that the concentration of NH_4-N since NH_4-N form of nitrogen readily oxidises into NO_3-N in aerobic soil condition (nitrification).

Table 6.1 Summary of analysis of variance (ANOVA) of the type of legume crop (L) and N fertiliser (F) treatments on NH_4-N and NO_3-N at various soil depths and growth stages of legume crops during the 2008 and 2009 cropping seasons. Significance of treatments is denoted as '*' for $p \leq 0.001$; '**' as $p \leq 0.01$; '*' for $p \leq 0.05$ and 'NS' for not significant.**

Parameters	Soil depths (cm)	Legume season 2008								
		Vegetative			Flowering			Harvesting		
		L	F	L×F	L	F	L×F	L	F	L×F
NH_4-N	0-20	NS	***	NS	NS	**	NS	NS	***	NS
	20-40	*	***	**	NS	**	NS	NS	***	NS
	40-70	NS	**	*	NS	NS	NS	NS	NS	NS
	70-100	NS	***	*	NS	NS	NS	NS	***	NS
NO_3-N	0-20	NS	***	NS	NS	***	*	NS	*	NS
	20-40	*	***	NS	NS	***	NS	NS	***	NS
	40-70	NS	***	NS	NS	*	NS	NS	***	NS
	70-100	NS	***	NS	NS	***	NS	NS	***	NS
Parameters	Soil depths (cm)	Legume season 2009								
		Vegetative			Flowering			Harvesting		
		L	F	L×F	L	F	L×F	L	F	L×F
NH_4-N	0-20	*	***	NS	NS	***	NS	NS	***	NS
	20-40	*	***	NS	NS	**	NS	NS	***	NS
	40-70	NS	***	NS	NS	NS	NS	NS	NS	NS
	70-100	NS	*	NS	NS	NS	NS	NS	*	NS
NO_3-N	0-20	NS	***	NS	NS	***	*	NS	NS	NS
	20-40	*	***	NS	NS	***	NS	NS	***	NS
	40-70	*	***	NS	NS	***	NS	NS	***	NS
	70-100	NS	**	NS	NS	***	NS	NS	***	NS

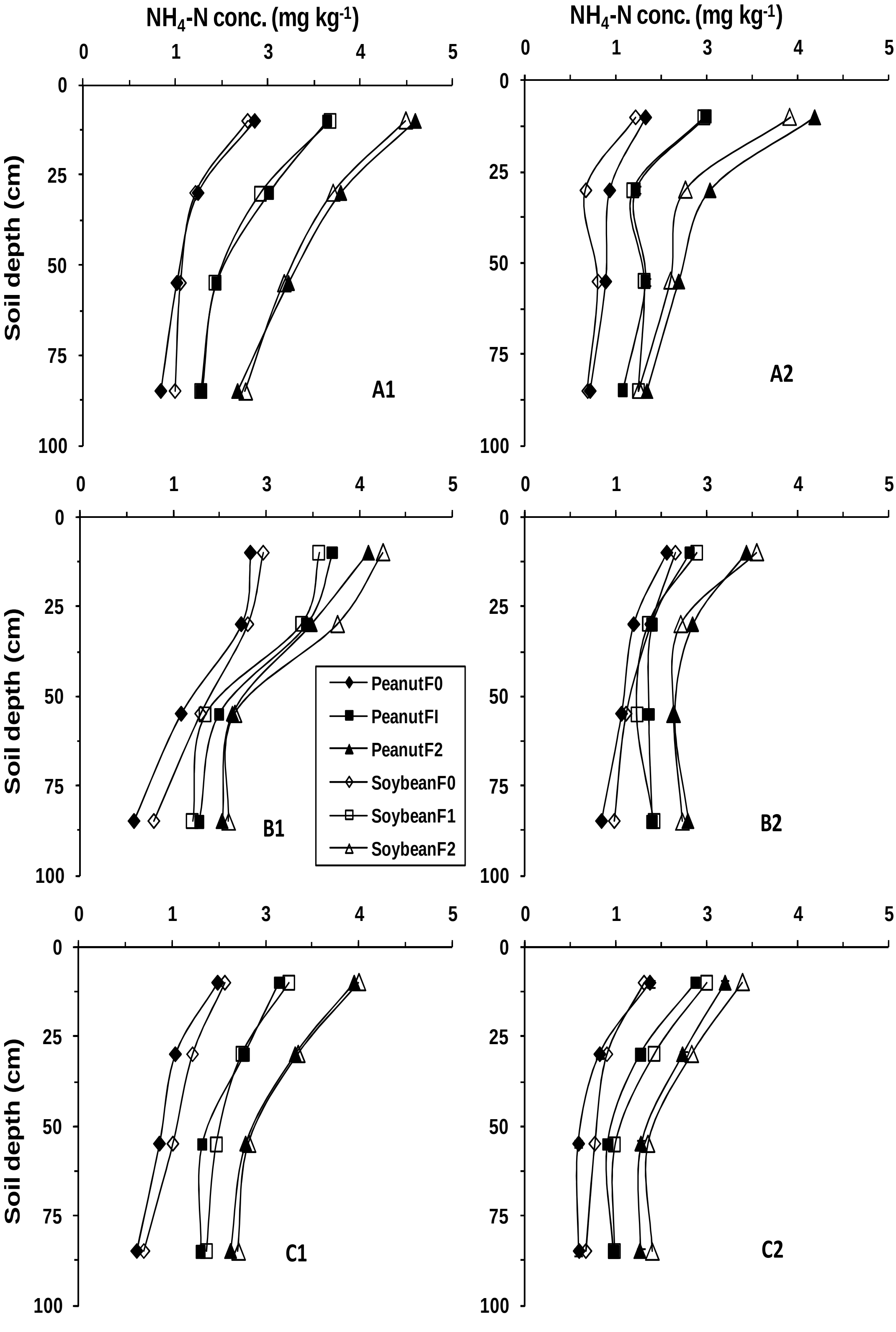

Figure 6.1 Spatial and temporal variation of NH_4-N concentration in soil as affected by N fertiliser application rates at vegetative (A; 31 DAS), flowering (B; 45 and 48 DAS for peanut and soybean respectively) and harvesting stages (C; 98 and 94 DAS for peanut and soybean, respectively) during 2008 (1) and 2009 (2)seasons.

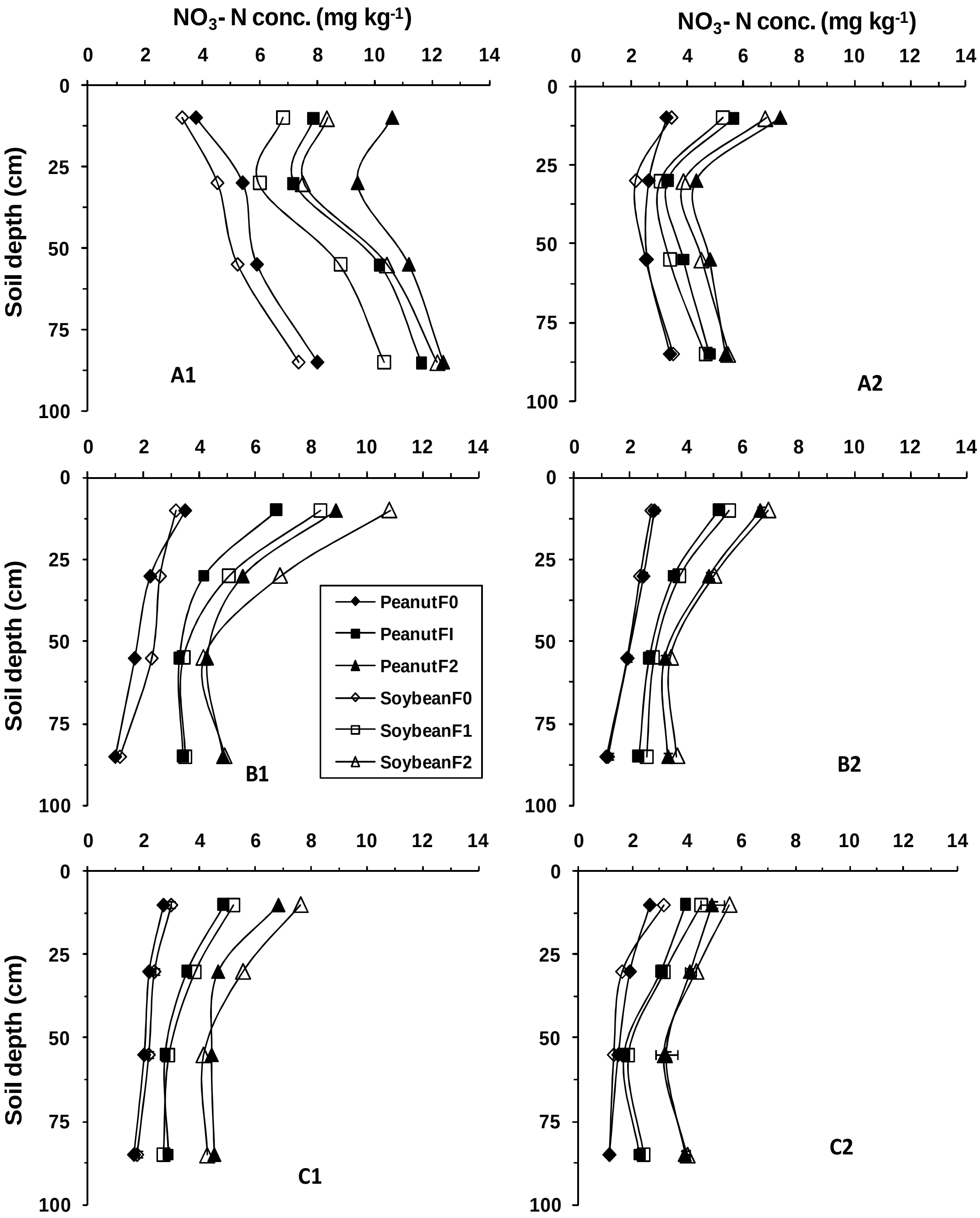

Figure 6.2 Spatial and temporal variation of NO_3-N concentration in soil as affected by N fertiliser application rates at vegetative (A; 31 DAS), flowering (B; 45 and 48 DAS for peanut and soybean respectively) and harvesting stages (C; 98 and 94 DAS for peanut and soybean, respectively) during (1) 2008 and (2) 2009 seasons.

During the early growth stage of the legume in both seasons (Fig. 6.2 A1 and A2; 31 DAS), the highest concentration of NO_3-N was oberved in 70-100 cm soil layer. The concentration of NO_3-N reduced by more than half at flowering stage (B1 and B2) in the same soil layer. Since NO_3-N is mobile and easily moved with percolating water, its concentration can be similar or higher in the subsoil (> 75 cm depth) than in the surface soil (at 25 cm depth) especially in the early period of growth in legumes (see Fig. 6.2 A1 and A2). NO_3-N can be also readily uptaken by the plant or lost beyond the root zone by leaching (Buresh and De Datta, 1991; George et al., 1992).

6.3.2 Nodulation

The influence of N fertiliser treatments on nodulation was examined during peanut and soybean growth periods in 2008 and 2009 seasons (Fig. 6.3 and 6.4). Nodules formation varied for both peanut and soybean growth throughout the growing seasons in both years and due to various N fertiliser treatments.

During the early growth stage of peanut in 2008, the number and weight of nodules were small and not affected significantly by N fertiliser application rates (Fig. 6.3). However, as peanut growth entered reproductive growth stage (55 DAS), nodule number was significantly high ($p = 0.032$) in F0 (no applied N) and decreased with increased N fertiliser application rates. Nonetheless, nodule weight was not affected by N fertiliser application rates at 55 DAS and the peak number and weight of nodules reached for peanut. This indicates that the maximum formation of nodules is reached at this stage. At this time, the reduction in nodule formation in peanut was 12% and 18%, respectively with fertiliser application rates of 12 and 24 kg N ha^{-1}. As the peanut crop approached physiological maturity, the rate of nodule formation slightly increased.

A similar trend in nodule formation was reported by Bell et al. (1994). The rate of N_2 fixation in peanut did not decline during the later stages of pod fill under irrigated and well fertilised conditions (with N fertiliser). Although the number and weight of nodules without N application (F0) were consistently higher than with increased N-application (F1 and F2), the difference were not significant. This is consistent with the observation of Reddy and Tanner (1980) who reported a decrease with the nodule number and dry weight of nodule, and also N-fixation of peanut inoculated with Rhizobium. Mean number and weight of nodules during peanut growth in 2008 and 2009 seasons was in order of F0>F1>F1. In the 2008 season, mean of nodules number during peanut growth were 256, 242 and 240 for F0, F1 and F2, respectively and mean of nodules weight were 1.88, 1.85 and 1.82 for F0, F1 and F2, respectively. In the 2009 season, mean of nodules number during peanut growth were 323, 302 and 293 for F0, F1 and F2 respectively and mean of nodules weight were 2.05, 2.01 and 1.96 for F0, F1 and F2, respectively.

For soybean, the variation of nodules number and weight were similar to peanut during 2008 season. Although nodule number varied over time, the effect of N fertiliser rates was not significantly different, except at 82 DAS (on 09 October 2008). The highest nodule number for soybean was observed at the pod development stage (R3 close to 61 DAS) and it reduced as soybean approached physiological maturity. This result supported the observation of Zapata et al. (1987) that maximum N fixation for soybean occurs between the R3 and R5 stages of soybean development. As soybean approached physiological maturity, the nodule number declined coinciding with R7 (beginning of pod maturity) growth stage. In general, nodule weight in soybean was similar to peanut (Fig. 6.3), although the nodule numbers were much lower. This indicated that soybean nodules were much larger than that of peanut. Unlike peanut, both weight and number of nodules appeared to decline in soybean although the reduction in nodule weight per plant appeared to be due to a reduction in the nodule number.

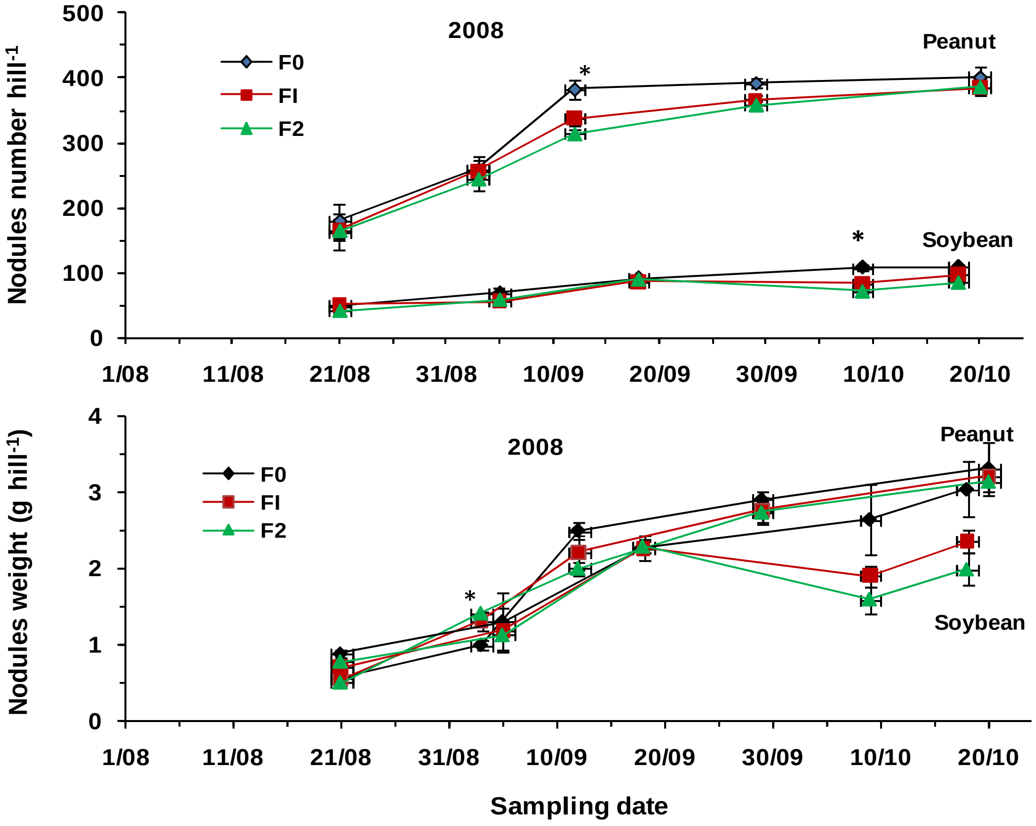

Figure 6.3 Mean weight and number of nodule/hill during soybean and peanut growth periods in 2008 season as affected by N fertiliser. * indicates $p \leq 0.05$.

The variation in nodule number and weight over the growth period in 2009 was similar to 2008 for both peanut and soybean (Fig. 6.3 and 6.4). However, nodule formation in 2008 was higher than that in 2009. Moreover, the peak time of nodule formation for both peanut and soybean occurred earlier in 2009 than in 2008. For both crops, the highest nodule numbers were observed at the beginning of pod formation (11 September 2008 or 55 DAS for peanut and 18 September 2008 or 61 DAS for soybean) that was approximately 13 days after flowering in 2008 (30 August 2009 or 42 DAS). This may have been affected by the concentration of NH_4-N and NO_3-N of soil that was slightly higher in 2008 than in 2009 (Fig. 6.5). If nitrate availability limits plant growth during the vegetative stage, root nodulation may occur earlier during the growth period (Lawn and Brun, 1974; Imsande, 1989).

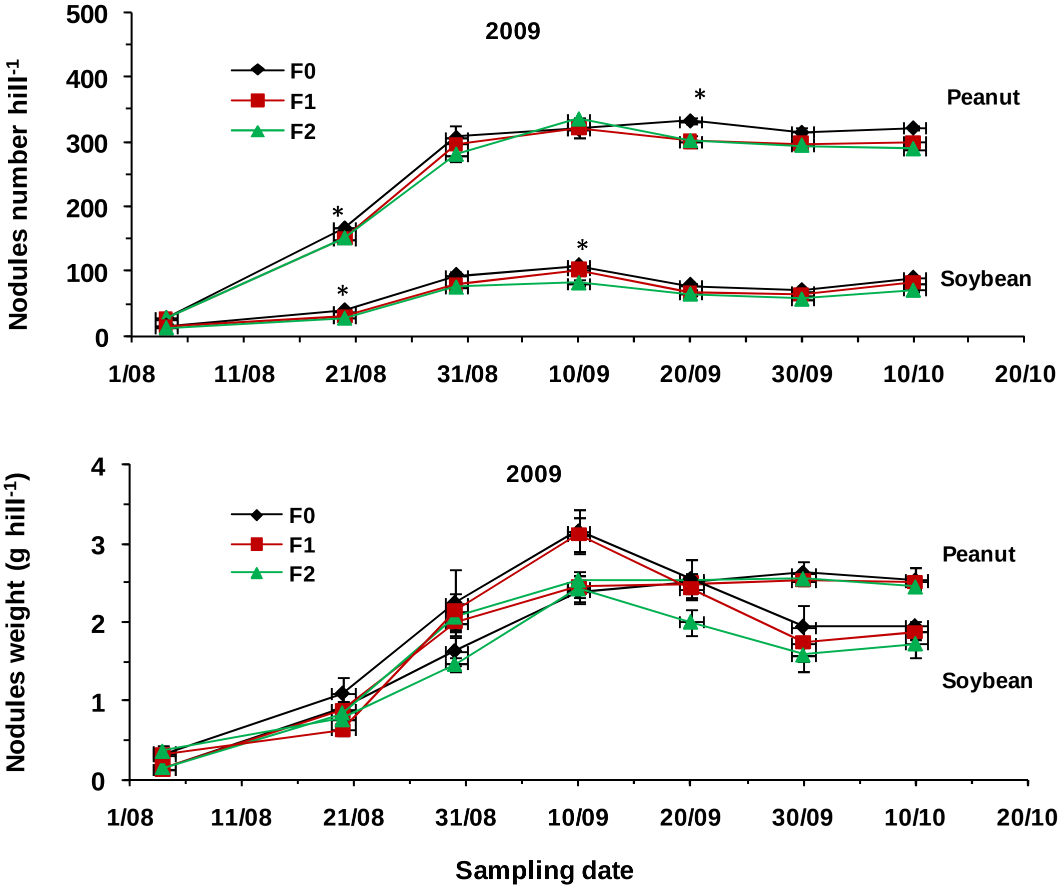

Figure 6.4 Mean weight and number of nodules/hill during soybean and peanut growth periods in 2009 season as affected by N fertiliser. * indicates $p \leq 0.05$.

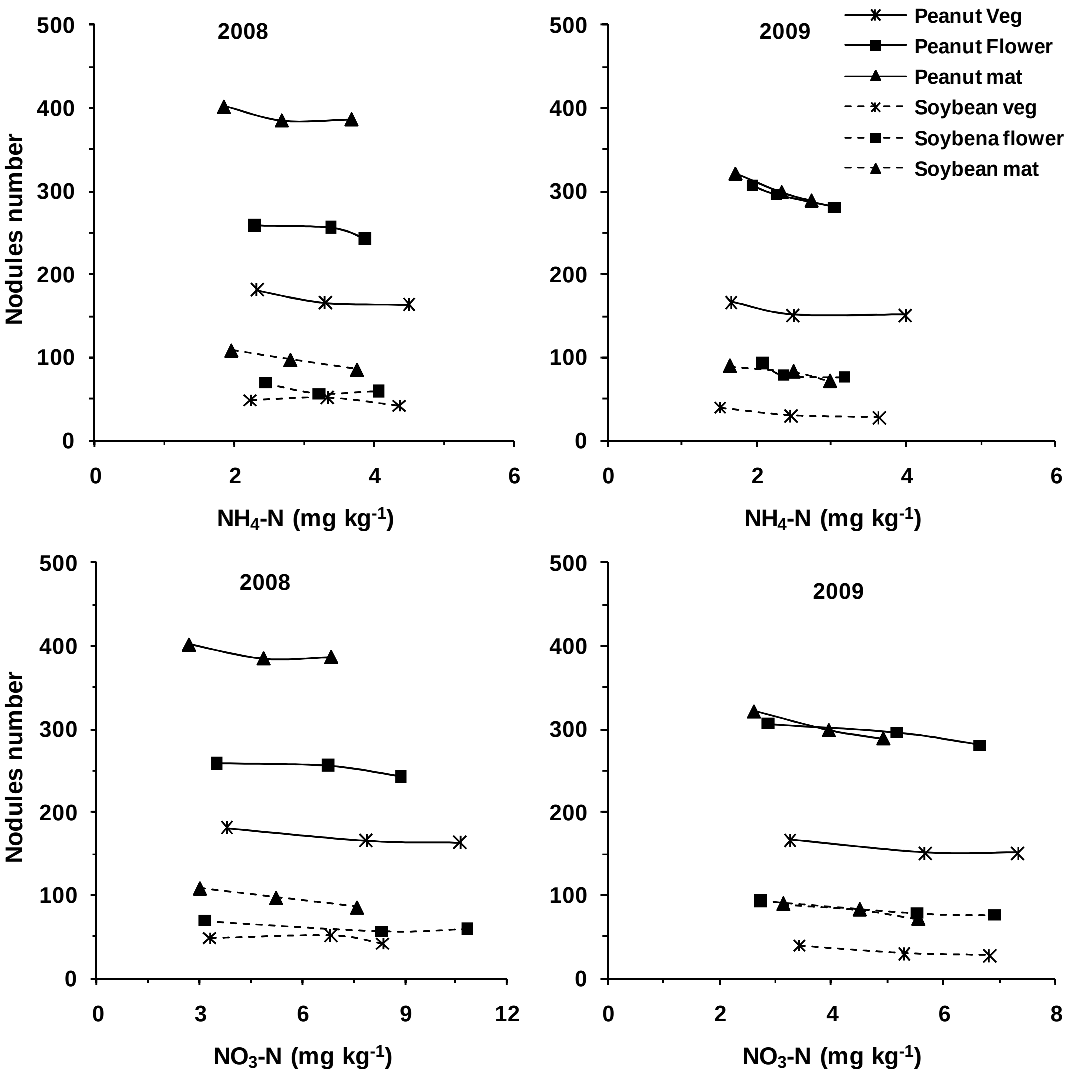

Figure 6.5 Relation between nodule numbers and NH_4-N and NO_3-N concentration in soils at 0-20 cm depth in peanut (solid lines) and soybean (dash lines) at various phenological stages (maximum vegetative (ж) flowering (■) and maturity (▲)) during 2008 and 2009 seasons.

The relationship between nodule numbers and NH_4-N and NO_3-N concentration in the soil at 0-20 cm depth at various growth stages of peanut and soybean in 2008 and 2009 season is presented in Fig. 6.5. Generally, there was an inverse relation between nodule number and NH_4-N and NO_3-N concentration in soil during the growth period of peanut and soybean. The number of nodules decreased with increasing in NH_4-N and NO_3-N concentration in soil, although this trend was not significant. Less significant effect of NH_4-N and NO_3-N concentration in soil on number and weight of nodule could be attributed to the small rates of N fertiliser applied, although the concentrations of NO_3-N and NH_4-N in soil were significantly increased as N fertiliser rates increased (Fig. 6.1 and 6.2). However, their significance may not affect the formation of nodules during peanut and soybean growth periods. Some previous researchers indicated that nodule formation was inhibited by application of N fertiliser to the growth media of legumes (Selamat and Gardner, 1985; Daimon et al., 1999; Taylor et al., 2005; Ray et al., 2006; Basu et al., 2008). Starling et al. (1998) found that nodule number and weight were reduced by application of 50 kg N ha^{-1} as starter N during the crop growth period of soybean. Moreover, Chen et al. (1992) reported that nitrogen fertiliser reduced nodule number, nodule weight and mean nodule size of soybean at three sites in Quebec, Canada. Daimon and Yoshioka (2001) reported that induction of NO_3-N to the growth media inhibited nodulation and nodule development of peanut.

6.3.3 Above ground biomass of legumes

The effect of various N fertiliser treatments on the above ground biomass at various growth stages of legumes in the 2008 and 2009 seasons is shown in Fig. 6.6. During the 2008 legume season, biomass samples were collected 5 times at various phenological stages of peanut and soybean to include one sample at vegetative stage and four samples at reproductive stage. During the early vegetative stage of peanut in the 2008 (plant sampled on 20-August), there was no significant effect of N fertiliser application rates on the above-ground biomass. However, above ground biomass increased significantly at flowering stage (sampled on 3rd September) and pod filling stage (sampled at 11th September) as N fertiliser application rates increased. This could be due to a significant increase in green leaf biomass and leaf area with increase in N fertiliser rates at flowering (Table 6.2). The above-ground biomass of peanut tended to increase as N fertiliser rates increased. At harvest, only stem biomass was significantly affected by N fertiliser rates. This indicates that N fertiliser tended to have a positive influence on vegetative growth and leaf area index as shown by Selamat and Gardner (1985) for nodulating and non-nodulating genotypes of peanut.

In soybean crop, above-ground biomass increased slightly although there was no overall significant effect of N-fertiliser rates. This suggests that reduced nodule formation due to an increase in N fertiliser rates (Fig. 6.4) did not cause significant reduction in above-ground biomass development during the growth period of both peanut and soybean legumes in rice-based cropping systems of the study site.

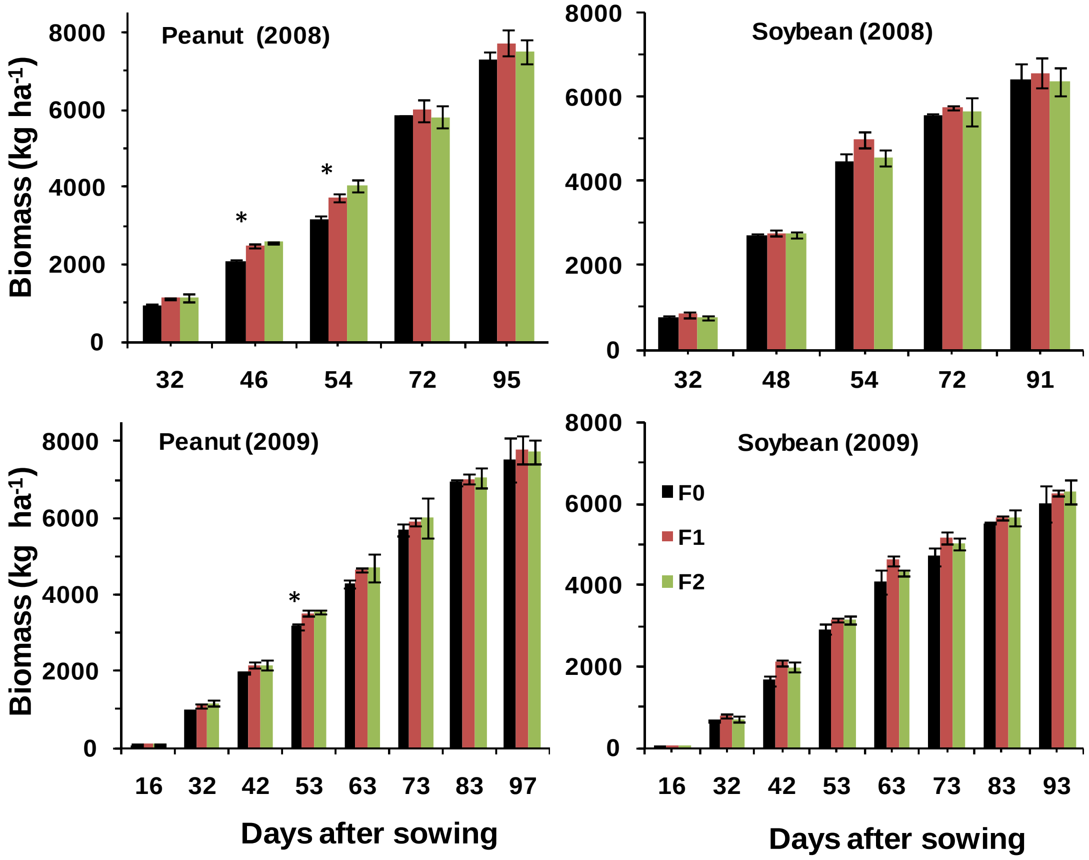

Figure 6.6 Biomass development during peanut and soybean growth periods as affected by N fertiliser treatments in 2008 and 2009 seasons.

In 2009, the crops were sampled more frequently (at 10-day intervals) to examine the effects of N fertiliser rates on legumes biomass (Fig. 6.6). These results showed that biomass of both peanut and soybean increase with increase in N fertiliser application rates but do not respond significantly to N fertiliser rates throughout the season except on some occasions e.g. at 53 DAS (at 10 September 2009) on peanut crop at flowering stage. This positive response of peanut at that stage to N fertiliser rates could be due to increased leaf biomass and leaf area (Table 6.2). These results indicate that applying N fertiliser to peanut and soybean crops in the rice-rice-legume crops sequence at the study site may increase biomass slightly but not at harvest.

Table 6.2 Summary of variance analysis (ANOVA) of legumes (L) and N fertiliser (F) treatments on green leaf biomass, stem biomass, leaf area hill^{-1}, green leaf total-N and stem total-N at varies growth stages in 2008 and 2009 crop seasons. Significance of treatments is denoted as '*' for $p \leq 0.001$; '**' as $p \leq 0.01$; '*' for $p \leq 0.05$ and 'NS' for not significant.**

Parameters	Legume crop season 2008								
	Vegetative			Flowering			Harvesting		
	L	F	L×F	L	F	L×F	L	F	L×F
Green leaf biomass	**	NS	NS	NS	*	*	N/A	NS	N/A
Stem biomass	*	NS	NS	NS	NS	NS	**	**	*
Leaf area hill^{-1}	*	*	NS	NS	*	NS	N/A	NS	N/A

Parameters	Legume crop season 2009								
	Vegetative			Flowering			Harvesting		
	L	F	L×F	L	F	L×F	L	F	L×F
Green leaf biomass	NS	NS	NS	*	**	NS	N/A	*	N/A
Stem biomass	***	NS	NS	NS	NS	NS	**	NS	NS
Leaf area hill^{-1}	NS	NS	NS	**	**	NS	N/A	NS	N/A

N/A = not applicable for split plot analysis as all leaf of soybean were senescenced and felt down at harvesting stages

Application of N fertiliser to legumes following the second rice crops may also restrict biological N fixation. Soybean is known to use biological N fixation to meet its N demand unless there are soil restrictions affecting normal nodule activity (Harper, 1987; Salvagiotti et al., 2008). Any part of the N that is not met by biological N-fixation may be derived from inorganic N sources in soil from mineralised organic matter and/or residual N from the previous crop. Pedersen (2004) stated that NO_3-N in soil is the main N source utilised by legumes up to the beginning of the pod development (R3). However, it may not affect maximum biomass for soybean at the R6 growth stage (full pod filling) as found in this study and others (Schmitt et al., 2001) as evident from biomass samples at the R6 growth stage (9 October 2008 and 10 October 2009; 82-83 DAS). A similar result has also been found by Barker and Sawyer (2005), that dry matter was not influenced by N fertiliser at the R6 soybean growth stage.

6.3.4 Yield and harvest index of legumes

Variations of yield and harvest index of legumes as affected by N fertiliser treatments in 2008 and 2009 seasons are presented in Table 6.3. Yield of legumes varied due to N fertiliser application rates in both seasons and ranged from 1970 kg ha^{-1} to 2019 kg ha^{-1} and from 1961 kg ha^{-1} to 2361 kg ha^{-1} for peanut and soybean, respectively. Yield of soybean in both 2008 and 2009 seasons increased at 12 kg N ha^{-1} applied (F1) but it decreased at 24 kg N ha^{-1} applied (F2) to lower than when not applied N (F0), although this trend was not significantly different. In peanut, grain yield decreased with increased N fertiliser application rates, although this was not significantly different. Yield of soybean was higher in 2008 than that in 2009, while yield of peanut was similar in both seasons. This finding was in agreement with other previous studies (Deibert et al. 1979; Peterson and Varvel 1989; Schmitt et al. 2001; Barker and Sawyer 2005). Schmitt et al. (2001) reported that there was no significant effect of fertiliser N on soybean seed yield at 12 sites of field experiment in St. Paul Minnesota, MN. Furthermore, Peterson and Varvel (1989) found reduced grain and dry matter yield with application of N fertilizer. Barker and Sawyer (2005) conducted a field experiment to determine the impact of N fertiliser applied to the soil at the beginning pod growth stage on soybean yield and grain quality for two years at five locations in Iowa. They reported that there was no significant effect of N fertiliser applied on grain yield, grain protein, oil contents, and fibre concentrations. Crusciol and Soratto (2009) reported that seed yield of peanut was not influenced by application of 60 kg N ha^{-1} on cover crops prior to peanut planting. The decrease in yield with increasing levels of fertiliser N rates observed in this experiment could be attributed to reduced formation of nodule in peanuts (Figure 6.3 and 6.4). The poorly developed symbiotic system might fail to meet the N requirements of the plant as a result of this early inhibition.

Harvest index (HI) for both peanut and soybean varied in both seasons ranging from 0.26 to 0.36 and 0.26 to 0.34 for peanut and soybean respectively. N fertiliser treatments did not significantly affect the HI for both peanut and soybean in both seasons. In addition, HI for both peanut and soybean was higher in the 2009 than that in the 2008 season. In the 2009 season, mean HI of peanut in this study was similar to that reported by Kiniry et al. (2005).

Table 6.3 Effect of N fertiliser on yield (kg ha^{-1}) and harvest index (HI) of peanut and soybean crops in 2008 and 2009 seasons. The values in bracket are indicate standard error (n=3). * indicate significant at p ≤0.05 and NS = not significant.

Legumes (L)	N rates (F) (kg ha^{-1})	Yield		Harvest index (HI)	
		2008	2009	2008	2009
Peanut	0	2110 (28)	2120 (87)	0.29 (0.01)	0.35 (0.03)
	12	2019 (38)	2109 (12)	0.26 (0.02)	0.36 (0.02)
	24	2010 (35)	1970 (90)	0.27 (0.02)	0.35 (0.01)
Soybean	0	2233 (113)	2039 (31)	0.29 (0.04)	0.34 (0.05)
	12	2361 (15)	2150 (29)	0.27 (0.01)	0.34 (0.04)
	24	2211 (125)	1961 (99)	0.26 (0.03)	0.31 (0.05)
F-test	Main plot (L)	NS	NS	NS	NS
	Subplot (F)	NS	NS	NS	NS
	L×F	NS	NS	NS	NS

6.3.5 Various aspects of crop N

The effects of N fertiliser treatments on seed-N uptake, nitrogen harvest index (NHI), total-N in seed and total-N uptake, are presented in Table 6.4 and 6.5. Total-N, total-N uptake, seed-N uptake and NHI varied with type of legume and N fertiliser treatments. Seed-N uptake, which was calculated by multiplying dry seed yield by total-N in seed, ranged from 122 to 157 kg N ha^{-1} and from 81 to 86 kg N ha^{-1} for soybean and peanut respectively. Seed-N uptake for soybean in this study was lower than that reported by Varvel and Peterson (1992) who found that seed N uptake ranged from 150 to 200 kg N ha^{-1}, probably due to a potential genetic effect of the cultivar used in this study and environmental conditions of crop to grow (Reddy et al. 1981). Seed-N uptake and NHI were not significantly affected by N fertiliser treatments, but legume types affected seed-N uptake and NHI in 2008 and 2009 seasons. Seed-N uptake and NHI in soybean was significantly higher than that in peanut, indicating greater N removed by soybean. NHI was 1.26 and 1.46 times greater than HI for peanut, and 3 and 2 times greater for soybean in 2008 and 2009 seasons respectively. This indicates that N removed from grain was higher than the other parts of crops. Bell et al. (1994) reported that NHI was 1.46 to 1.80 times greater than HI in various cultivars of peanut.

Table 6.4 The effect of N fertiliser on seed N uptake and N harvest index (NHI) of peanut and soybean crops in 2008 and 2009 season. The values in bracket are indicate standard error (n=3). * indicate significant at p ≤0.05 and NS = not significant.

Legumes (L)	N rates (F) (kg ha^{-1})	Seed-N uptake (kg N ha^{-1})		N harvest index (NHI)	
		2008	2009	2008	2009
Peanut	0	82 (3.5)	85 (3.6)	0.38 (0.02)	0.55 (0.04)
	12	83 (3.7)	86 (5.5)	0.32 (0.02)	0.50 (0.01)
	24	83 (2.4)	81 (7.3)	0.32 (0.01)	0.48 (0.03)
Soybean	0	150 (12.9)	124 (1.3)	0.83 (0.01)	0.65 (0.02)
	12	157 (1.6)	133 (0.6)	0.84 (0.01)	0.67 (0.02)
	24	151 (9.8)	122 (5.9)	0.83 (0.01)	0.65 (0.02)
F-test	Main plot (L)	*	*	*	*
	Subplot (F)	NS	NS	NS	NS
	L×F	NS	NS	NS	NS

Table 6.5 The effect of N fertiliser treatments on total-N and total-N uptake of peanut and soybean crops in 2008 and 2009 seasons. The values in bracket are indicate standard error (n=3). * indicates significant at P ≤0.05 and NS = not significant.

Legumes (L)	N rates (F) (kg ha^{-1})	Total-N		Total-N uptake	
		2008	2009	2008	2009
Peanut	0	2.37 (0.07)	2.50 (0.02)	218 (6.5)	216 (3.6)
	12	2.72 (0.04)	2.63 (0.05)	255 (9.4)	226 (1.9)
	24	2.86 (0.09)	2.68 (0.02)	263 (10.3)	230 (3.2)
Soybean	0	3.21 (0.09)	3.14 (0.07)	180 (13.7)	215 (6.7)
	12	3.28 (0.05)	3.17 (0.03)	189 (2.6)	224 (2.1)
	24	3.32 (0.02)	3.21 (0.05)	182 (10.8)	209 (5.9)
F-test	Main plot (L)	*	*	*	NS
	Subplot (F)	*	NS	*	*
	L×F	NS	NS	NS	NS

Total-N and total-N uptake varied with N fertiliser treatments and legume types. Total-N and total-N uptake increased as N fertiliser rates increased in both peanut and soybean crops, except at 2009 season for total-N (Table 6.5). Total N uptake, which was calculated by multiplying dry biomass by total-N, ranged from 180 to 224 kg N ha^{-1} and from 210 – 263 kg N ha^{-1} for soybean and peanut respectively. Although total-N and N-uptake of peanut and soybean generally increased with N fertiliser application, seed-N uptake and NHI was not affected by N fertiliser.

6.4 Concluding remarks

Nitrogen fertiliser influenced NH_4-N and NO_3-N concentrations in soil during the growth period of each legume. Legume types appeared to have influence on NH_4-N and NO_3-N concentration in soil at the vegetative stage of growth and there was no significant influence as growth progressed. Nodule number and weight decreased as N fertiliser rates increased during the growth period of legume crops, although this trend was not significant. Nodule formation during the vegetative stage of legume was small but it peaked between flowering and pod formation stages. The rate of nodule formation declined in soybean while a slightly increased in peanut as the crops approached physiological maturity. N fertiliser appeared to have a significant effect on biomass development between flowering and pod filling stages of peanut growth and no significant effect at harvesting stage. In soybean, there was no significant effect of N fertilisers on biomass. N fertiliser treatment did not significantly affect the seed yield, harvest index or N harvest index for both peanut and soybean legumes, although total-N and total-N uptake was affected by N fertiliser treatments. These results reveal that applying N fertiliser to peanut and soybean crops in the rice-rice-legume crops sequence in the study site would not increase biomass and yield substantially. The implication of this study is farmers may consider not applying N fertiliser during peanut and soybean season in the region represented by this study site.

CHAPTER VII

Simulation of tropical lowland rice-based cropping systems at various nitrogen and water managements

7.1 Introduction

Rice is one of the biggest users of the world's developed freshwater resources because it is mostly grown under flooded or submerged condition (Tuong and Bouman, 2003; Bouman and Tuong, 2001; Tuong et al., 2005). However, water is becoming increasingly scarce raising concerns about the sustainability of irrigated agriculture (Rijsberman, 2006). Many rainfed areas are already drought-prone under present climatic conditions and are likely to experience more intense and more frequent drought events in the future due to climate change (Wassmann et al., 2009). Increasing water productivity is especially important because many processes in rice production area are related to water (Bouman, 2007). Therefore, efforts to reduce water use are of great significance in the rice-based cropping systems.

Lowland rice-based cropping systems are characterised by the alternation of anaerobic and aerobic soil conditions during flooded rice crops in the wet season and non-flooded crops in the dry season (Kundu and Ladha, 1999; De Data, 1995; Ladha et al., 1996; George et al., 1993). These conditions strongly affect microbial C and N dynamics (Fierer and Schimel, 2002; Gu et al., 2009) and increase inorganic soil nitrogen during rewetting (Qiu and McComb, 1996; Appel, 1998; Lundquist et al., 1999). Excess mineral N that may not be taken up by the crop may be lost through denitrification or leaching (George et al., 1993; Buresh and De Data, 1991; Reddy et al., 1989; Qiu and McComb, 1996). These complex processes need to be better understood and quantified as a basis for improvements in crop management in rice-based farming systems to increase yields and nitrogen and water use efficiencies (Jing et al., 2010). Modelling is an important and effective tool for explicitly describing the relationships among the components of complex systems. Modelling contributes to increased insight into relevant processes and their interactions, and can be applied to study effects of crop management, and to explore possible consequences of management modifications (van Keulen, 2001). The challenges for application of existing models to simulate rice-rice-legume crop rotation systems are the regular alternation between anaerobic and aerobic conditions and associated consequences for decomposition of soil organic matter, nitrogen transformation and translocation (Probert, 2002).

Cropping system models integrate data management and knowledge of soil, plant and atmospheric systems to allow simulation of cropping system over a wide range of environments and management practices (Larson et al., 1996; Pala et al., 1996; Cavero et al., 1998; Hunt and Boote 1998; Alves and Nortcliff 2000; Mailhol et al., 2001). This makes them valuable tools for agricultural professionals around the world (Bouman et al., 1996; Jones et al., 2003). Development and evaluation of models require all of the aforementioned types of data together with additional data such as time-series data on crop development, soil moisture, and soil nutrients as well as yield and yield components (Hunt and Boote 1998). For adaptation and application of state-of-the-art agricultural system models for such purposes, they need to be well-calibrated and thoroughly validated for their performance in the agroclimate of the region of interest.

There have been intensive efforts to study the rice production system resulting in the development of several rice simulation models (McMennamy and O’Toole 1983; Godwin and Jones 1991; Horie et al., 1992; Aggarwal et al., 1997; Bouman et al., 2001). ORYZA2000 is one of the most widely used and intensively tested simulation models for rice developed at the International Rice Research Institute (IRRI, Philippines) in collaboration with Wageningen University (The Netherlands). The model has capability to simulate crop management options such as irrigation and nitrogen management (Bouman et al., 2001; Bouman and van Laar, 2006). (). However, the ORYZA2000 model is based for rice crop in single growing season. The model may not simulate crops sequence under any cropping system, which may include rice. Furthermore, the model does not able to simulate the dynamic aspects of nutrients, especially nitrogen, and soil water for the sequences of crops and fallows within a cropping system. There is an increasing demand for the model to simulate rice-based cropping systems, especially in Asia. Such the model will allow investigation of nitrogen dynamics, crop sequence, intercropping, crop residue management and soil and water management.

Cropping systems models such as Agricultural Production Systems sIMulator, APSIM (Keating et al., 2003) describe the dynamics of crop growth, soil water, soil nutrients, and plant residues as a function of climate, cropping history and soil/crop management on a daily time step. Through the linking of crop growth with soil processes, APSIM is particularly suited for the evaluation of likely impacts of alternative management practices on the soil resource and crop productivity. The model has been used successfully in the search for strategies for more efficient production, improved risk management, crop adaptation, and sustainable production (Keating et al., 2003). However, APSIM was developed for dryland farming systems rather than lowland paddy farming systems and not for rice simulation in either dryland, or paddy lowland (Keating et al., 2003). Paddy lowland is usually more complex in terms of nitrogen dynamics because it includes nitrogen transformation and leaching between water-ponded surface layers and oxidized and reduced soil layers. Currently the model is lacking the capability to simulate those processes (Keating et al., 2003; Zhang et al., 2007).

New systems elements which were required in APSIM (Keating et al., 2003) to simulate the complete C and N dynamics in complex farming systems involving rice-rice-legumes crops sequence where anaerobic and aerobic systems occur has been recently developed by Gaydon et al. (2009). This new capability of APSIM-Oryza to simulate crop rotations in rice-based cropping systems has undergone limited testing and validation to this point under wide variety of field management and cropping systems. In a previous study, Zhang et al. (2007) tested the APSIM-Oryza model to simulate nitrogen dynamics of paddy soil by using existing nitrogen module in the Oryza2000 model, but found that the model was not able to simulate the nitrogen response using the simple book keeping N module in APSIM-Oryza. This was probably due to the complex nitrogen dynamics including transformation and translocation in reduced layers that occurred particularly in paddy soil which differ from those in dryland soil (Godwin and Singh, 1998). In this situation, the versatility of the APSIM-Oryza model can be increased if it is able to simulate the processes of nitrogen dynamics in paddy lowland and is able to correctly simulate the productivity of rice-rice-legume rotation system in lowland Asian countries. The objectives of this study were:

1. To parameterise and calibrate the APSIM-Oryza model in lowland rice-based cropping systems in tropical climate;

2. To evaluate the performance of the model at various nitrogen and water managements.
3. To improve understanding of water and N dynamics in continuously submerged and alternately submerged and non-submerged irrigation water management related to the model.

7.2 Material and methods

7.2.1 Description of field experiment

The details of field experiment for calibrating and validating the APSIM-Oryza model are presented in Chapter 3. Data from first 2007-2008 and second 2008-2009 years of field experiment were used to parameterise and calibrate, and validate the model respectively. Briefly, the experiment was laid out in a randomised split plot design with water management (continuously submerged and alternate submerged and non-submerged, hereafter referred as CS and ASNS respectively) as main plot and fertiliser rates (0, 70 and 140 kg N ha^{-1}) as subplot with three replications. First rice was planted in wet season (transplanted on 13th November 2007 and harvested on 5th March 2008). Plant and soil samples were collected at four main phenological stages of rice (tillering, panicle initiation, flowering and harvesting). Soil samples were taken up to 100 cm depth, fractioned to 4 layers (0-20, 20-40, 40-70 and 70-100 cm) and each layer was analysed for NH_4-N, NO_3-N, total-N, and organic carbon (OC). Plant samples were measured for dry biomass and total-N. At harvesting stage, rice was sampled at 100 m^2 to obtain grain yield, converted to kg grain yield ha^{-1} and presented at 14% water content. Second rice was transplanted at approximately one month after first rice was harvested which was at the end of wet season to dry season (transplanted on 1st April 2008 and harvested on 16th July 2008). The cultivation management and sampling procedures were similar to first rice season. Immediately after the second rice crop was harvested, legumes were sown at the same plot to rice. The experimental design was similar to rice with legume types as the main plot replacing CS and ASNS treatments with peanut and soybean respectively and fertiliser rates as subplot. Legume crops were sown on 19th July 2008 and harvested on 18th and 24th October 2008 for soybean and peanut respectively. Legume crops and soil were sampled at three main phenological stages (maximum vegetative, flowering and harvesting). Legumes crops were separated to green leave, stem, dead leave and pod if any and measured dry biomass and total-N. Soil samples were treated similar to soil sampling at rice season. The cultivation management and sampling procedures were repeated in the second year of 2008-2009 experiment of rice-rice-legume crop sequence. Additional biomass sampling for legumes crops were collected every 10 days starting from vegetative stage onwards. Summary of experimental inputs for the model calibration and validation are presented in the Table 3.2 of Chapter 3.

7.2.2 Model overview and description

APSIM is a dynamic crop growth model that combines biophysical and management modules within a central engine to simulate cropping systems, rotations, fallowing, crop and environmental dynamics (McCown et al. 1996; Keating et al. 2003). APSIM-Oryza allows simulating development of rice such as transplanting, crop growth, yield, nitrogen uptake of crop, and deals with other important features of a rice cropping system such as fertilisation, nitrogen dynamic of soil, field management issues and rotation effects on crop residue over a long period.

The key APSIM (version 7.1) modules deployed in this study were Rice (*Oryza sativa* L), Peanut (*Archis hypogaea* L) and Soybean (*Glicin max* Mer.), SoilN (soil nitrogen), SoilWat (soil water balance), Surface Organic Matter and Pond. These modules were linked via a central engine of APSIM to simulate the rice based cropping systems .These modules are briefly described below and logic commands of rice-rice-legume crops sequence simulation in the general manager of APSIM are described in Appendix 1.

7.2.2.1 Rice module

The rice module of APSIM, was derived from ORYZA2000 rice crop growth model (Bouman et al. 2001), which simulates phenological development, biomass accumulation, yield, and nitrogen accumulation in response to temperature, radiation, photoperiod, soil water, and nitrogen supply in a daily time-step (Keating et al. 2003). The details of the rice module are described by Bouman et al. (2001). Briefly, the model calculates growth and development of rice as a function of daily weather data, crop characteristics, and management parameters. The total daily rate of CO_2 assimilation is estimated from the daily incoming radiation, temperature, and leaf area index (LAI) based on an assumed sinusoidal pattern of radiation over the day and exponential light within canopy. The integration over LAI of the canopy and over the day gives the daily CO_2 assimilation rate. Maintenance respiration requirements are subtracted from the gross assimilation rate to obtain net daily growth. The dry matter produced is partitioned among the various plant organs including roots, leaves, stem, and storage organ (panicle) as a function of development stage (DS). The phenological development stage is tracked as a function of mean ambient daily temperature and photoperiod. The rice crop module has four phenological development stages:

1. Juvenile stage, starting from emergence (DS = 0) to start of photoperiod-sensitive phase (DS = 0.4),
2. Photoperiod-sensitive stage, starting from DS = 0.4 to panicle initiation (DS = 0.65),
3. Panicle development stage, starting from DS = 0.65 to 50% flowering (DS = 1.0), and
4. Grain-fill stage, starting from DS = 1.0 to physiological maturity (DS = 2.0).

Each of these four stages has variety-specific development rate constants (DRC). Differences among varieties in total duration are caused primarily by differences in the duration of the juvenile phase. Sub-optimal photoperiod less than the optimal photoperiod, results in a longer photoperiod sensitive phase. In grain crops, carbohydrate production during grain-fill can be higher or lower than the storage capacity of grains, which is determined by the number and maximum growth rate of grains. The number of spikelets at flowering is calculated from biomass accumulation from panicle initiation up to first flowering. Spikelet sterility due to either too-high or too-low temperature is considered. Leaf area growth includes a source- and sink-limited phase. In the early stage, leaf area grows exponentially as a function of temperature sum, and relative leaf growth rate. After LAI is larger than one, increase in leaf area during the linear phase is calculated from increase in leaf mass and specific leaf area (SLA) that depends on DS. From flowering onwards, leaf loss rate is accounted for using a DS dependent loss rate factor and green leaf biomass. When the rice crop is transplanted, LAI and all biomass values are reset based on planting density after transplanting relative to plant density in the seedbed.

Crop growth resumes only after a ‘transplanting shock’ has elapsed duration of which has a linear correspondence with seedling age at transplanting. In transplanted rice, transplanting shock also causes a delay in phenological development that depends on seedling age (Bouman et al., 2001; Bouman and van Laar, 2006).

7.2.2.2 Peanut and soybean modules

The peanut and soybean crop modules of APSIM simulate phenological development, biomass accumulation, yield, and nitrogen accumulation in response to temperature, radiation, photoperiod, soil water, and nitrogen supply in a daily time-step. Keating et al. (2003) outlined the crop module, which provides references for more detailed crop simulation descriptions. In brief, approaches used in modelling crop processes balance the need for comprehensive description of the observed variation in crop performance across diverse production environments and the need to avoid large numbers of parameters that are difficult to measure. Crop development is controlled by temperature (thermal degree days) and photoperiod. Thermal time accumulations were derived using the algorithm described by Jones and Kiniry (1986) using observed phenology and weather data. Growth development parameters of peanut and soybean have been described in details by Roberston et al. (2002). Potential biomass growth is a function of the intercepted radiation and the radiation-use efficiency. Water-limited growth is a function of water supply and the transpiration efficiency of the crop, which varies daily as a function of vapour pressure deficit. Actual biomass increase is simulated from either potential or water-limited growth as modified by temperature and N stresses. Daily weather data such as minimum and maximum temperature, radiation, and rainfall were collected from the site of experiment from 1997-2009.

7.2.2.3 SoilN module

The SoilN module simulates the transformations of C and N in the soil. These include soil organic matter decomposition, N immobilisation–mineralisation, nitrification and denitrification. The conceptual soil organic carbon pool that represented in the module is treated as a three-pool system; HUM, BIOM and FOM (Probert et al., 1998). HUM is the more stable component while BIOM generally represents the more active and labile soil microbial biomass and microbial products.

FOM is the fresh soil organic matter pool including plant roots and aboveground matter incorporated into soil through tillage. Flows between these pools are regulated by the C:N ratio of the receiving pool. To allow for slower rates of decomposition in the deeper soil layers, part of the soil organic matter is considered to be non-susceptible to microbial decomposition over the growing season (Keating et al. 2003).

Gaydon et al. (2009) has modified the organic matter decomposition rate constant as input parameters to APSIM SoilN module with two values instead of one; a value for aerobic conditions and a value for anaerobic conditions which was adapted from Jing et al. (2007). Transformation of C and N under aerobic condition is different to anaerobic condition. Under anaerobic conditions, organic matter cycling takes place in the absence of oxygen with rate a 2-3 times lower than in aerobic condition (DeBusk and Reddy, 1998; Kirk & Olk, 2000; Jing et al., 2007; Jing et al., 2010). It has assumed that anaerobic soil conditions develop rapidly after flooding and there is no lag whilst the micro-organisms adapt to the changed conditions. That is a new APSIM-SoilN code structure enabling seamless switching between aerobic and anaerobic conditions within the soil (Gaydon et al., 2009).

7.2.2.4 SoilWat module

SoilWat module simulates soil water dynamics in the soil systems. Soil water dynamics between soil layers were defined by the cascading water balance method (Probert et al., 1998, Richie, 1998; Keating et al., 2003). Its characteristics in the model are specified by the drained upper limit (DUL), lower limit of plant extractable water (LL15) and saturated water content (SAT). Soil water content measurements before rice transplanting defined the initial soil water content of the soil.

7.2.2.5 Pond module

Pond module is a new module in the APSIM model that has been recently developed and described in details by Gaydon et al. (2009). In brief, the APSIM-Pond module simulates key chemical and biological processes occurring within a ponded layer of surface water. Pond temperature and pH are important variables governing chemical and biological processes. In the pond module, a fully dynamic pond temperature and pH balance is maintained and calculated on a two-hourly timestep basis to capture the rapid reaction rates. The chemical processes in the ponded and soil layers are modelled by APSIM-Pond and APSIM-SoilN respectively. These two modules communicate with each other on a daily basis to transfer nutrients via a central engine according to standard APSIM protocols (Keating et al. 2003). It assumes that N is only available for uptake by the rice crop once it is in the soil layers (i.e. from the SoilN module).

The APSIM-Pond module is a transient module in any simulation. It becomes active whenever the soil water balance module (SoilWat) determines that water is ponded on the soil surface. The APSIM-Pond module only handles the chemical processes while the soil water balance module simulates the water balance of pond and soil alike, as a continuum. When rainfall and/or irrigation cease, the pond depth will decrease by infiltration into the soil until there is no pond at all. APSIM-Pond checks with the water balance module on a daily basis to see whether it should be ‘active’ or not, as well as obtaining information on evaporation and current ponded depth. Effectively, the APSIM-Pond module may be conceptualised as a ‘filter’ of nutrients – not allowing all applied N to reach the crop, and simulating loss (but also) gain mechanisms for both C and N. If the pond has ‘drained down’, the APSIM-Pond module becomes inactive and the nutrient ‘filter’ is removed. When the pond is hydraulically re-established (as determined by the soil water balance module), APSIM-Pond becomes active and once again begins its role filtering N and potentially producing new C and N in the system through algal growth (if conditions are appropriate). Chemical processes in pond are discussed in details by Gaydon et al. (2009) and briefly explained below include urea hydrolysis, nitrification, ammonia volatilisation, alga growth and turnover, immobilization of pond mineral N, and flux of solutes to/from soil.

A. *Urea hydrolysis.* The breakdown of applied urea fertiliser to NH_4^+ is described as a function of pond temperature and a soil-determined hydrolysis rate (a function of organic carbon in top soil layer) or an algal activity determined rate, whichever is greater (Godwin and Singh, 1991).

B. *Nitrification.* Nitrification of NH_4^+ to NO_3^- is calculated as a function of pond temperature and pH.

C. *Denitrification*. This process is controlled by soil moisture and redox potential (Steven et al., 1998), temperature and pH (Heinen, 2006; Ashby et al., 1998). Denitrification is calculated as function of pond temperature and pH

***D.** Ammonia volatilization.* Pond ammonia (NH_3) exists in both aqueous and gaseous forms in equilibrium. The overall pond ammonia concentration is calculated from the pond ammonium (NH_4^+) concentration as a function of pond temperature and pH. The partial pressure of ammonia is calculated from the overall ammonia concentration as a function of pond temperature. This partial pressure of ammonia provides the potential for ammonia volatilization and N-loss to the atmosphere. This loss potential is a function of wind and pond depth. In the absence of wind data, evaporation is used as a surrogate (Godwin and Singh, 1991).

***E.** Algae growth and turnover.* Godwin and Singh (1991) described the calculation of an algal activity factor, which influences urea hydrolysis and floodwater pH. This factor is used here with additional calculation of the daily algal growth and accumulated biomass as follows:

$$\text{dlt\_pab} = \text{maxrate\_pab} \times \text{algact} \qquad 7.1$$

where *dlt_pab* is the daily growth of algae (kg ha^{-1}), *maxrate_pab* is the maximum daily growth rate of algae, which is about 20 kg ha^{-1} day^{-1} (Roger, 1996), and *algact* is the daily algal activity factor (Godwin and Singh 1991). Pond algal biomass (PAB) is allowed to reach a maximum of 500 kg dry weight ha^{-1}, with C content of 40% and C:N of approximately 8 (Roger, 1996). As PAB accumulates biomass, N uptake is from mineral N in the floodwater. When N demand outstrips supply, it has assumed that the shortfall is made up via N fixation, and algal growth remains unaffected. A significant new element of APSIM-Pond is the description of algal turnover. The natural limitation on algal growth is rice canopy closure and algal deprivation of solar radiation. If the maximum algal biomass of 500 kg ha^{-1} is reached before full canopy closure, further algal production is theoretically possible, and it has assumed that subsequent potential daily algal growth is matched by algal senescence which is added to the APSIM-SurfaceOM pool on a daily basis. This assumption was made to partially address the criticism of CERES-Rice's inability to capture long-term trends in soil organic carbon. In simulation of long-term rice experiments at IRRI, CERES-Rice simulated a rundown in soil organic carbon, when in fact none was measured. Another key element in addressing this issue is the addition of the complete PAB biomass to the surface organic matter pool after draining-down of the rice paddy. There it can decompose or be incorporated into the soil as per standard APSIM residue simulation. To simulate situations where live algae may sit viably on the wet surface of the soil during intermittent of drained period of a rice pond (such as in alternate submerged and non-submerged (ASNS) irrigation practice (Bouman et al., 2007) and then spring back to life on re-flooding, there is no add the PAB to the ASPIM surface organic matter pool until a period of 5 days with no ponding has passed.

F. *Immobilisation of pond mineral N.* When surface organic matter is decomposed in traditional dryland APSIM simulations, the APSIM-SurfaceOM module creates an immobilisation demand which it attempts to satisfy from APSIM-SoilN. When APSIM-Pond is present, this demand is sought from APSIM-Pond mineral N pools. Similarly, mineral N released in decomposition becomes part of the APSIM-Pond mineral N pools. If a pond is present, the moisture factor for decomposition of residues is set to 0.5 to account for slower decomposition in water.

G. *Flux of solutes to/from soil.* APSIM-Pond pools of urea, NH_4^+ and NO_3^- are transferred to the soil on a daily basis via the processes of mass flow, diffusion, and via adsorption in the case of NH_4^+ ion. For NO_3-N and urea, which are highly soluble, concentrations in the pond are compared with those in soil solution. When the concentrations are different in the two compartments, a “diffusion process” is invoked to determine the flux. The flux of NH_4^+ ion between pond and soil depend on the soil cation exchange capacity (CEC) (Godwin and Singh 1998). This is a new APSIM-SoilN input parameter.

7.2.3 Model parameterisation and calibration

7.2.3.1 Rice module

Rice variety of ‘cigeulis’ was calibrated using the IR72 standard crop parameters (Bouman et al., 2001) following the procedure described by Bouman and Van Laar (2006). Data from the 2007/2008 field experiment were used to parameterise the rice module. Phenological development rates were calculated using the recorded dates of emergence, maximum tillering, panicle initiation, flowering, and maturity in the field experiment. The specific leaf area was computed from measured green leaf surface area and green leaf dry weight (see Chapter III, section 3.2.7.4). The dry matter partitioning factors were first estimated from the measured biomass of leaves, stems, and panicles, and further finetuned by model fitting (Table 7.1). Refining the parameter value was done until simulated biomass and phenological development stages values best agreed with measured values. All other crop parameters were parameterised with similar methods as in ORYZA2000's standard crop data file for IR72 (Bouman et al., 2001).

Flowering stage is an important phenological event for crop management and is strongly affected by the photoperiod and that a short day length during the photoperiod-sensitive phase accelerates the flowering process and vice versa (Yin *et al*. 1997; Yin and Kropff 1998). In the ORYZA2000 model, the photoperiod sensitivity of rice is quantified by a variety specific factor derived from a non-photoperiod-sensitive variety (IR72). Due to lack of measurements in this study, the default values for IR72 were used for APSIM model.

Table 7.1 Calibrated phenological development rate of rice variety of 'Ciugelis'

Acronym	Definition of parameters/variables	Values	Unit
DVRJ	Development rate in juvenile phase.	600	$^{o}Cd^{-1}$
DVRI	Development rate in photoperiod-sensitive phase.	570	$^{o}Cd^{-1}$
DVRP	Development rate in panicle development	884	$^{o}Cd^{-1}$
DVRR	Development rate in reproductive phase.	1580	$^{o}Cd^{-1}$
MOPP	Maximum optimum photoperiod	11.50	h
PPSE	Photoperiod sensitivity	default	h^{-1}

7.2.3.2 Peanut and soybean modules

Local varieties of 'garuda and wilis' for peanut and soybean respectively were used in this study and parameterised using standard crop parameters of 'Virginia Bunch and Davis' varieties, respectively. Peanut and soybean data from the 2008 field experiment were used to parameterise and calibrate the crop components in the model. Detailed crop phenology recorded during this experiment served to compute the thermal time durations between crop phases from germination to maturity. The method for calibrating peanut and soybean modules was similar to rice module. The calibrated values of peanut and soybean phenological rates are presented in Table 7.2.

Table 7.2 Calibrated phenological development rate of peanut variety of 'Garuda "and soybean variety of 'Wilis' for model simulation

Acronym	Definition of parameters/variables	Values		Unit
		Peanut	Soybean	
y_hi_incr	Rate of harvest index.	0.0058	0.015	1/day
TT_Emergence units	TT from emergence to end of juvenile	5.0	70.0	$^oCd^{-1}$
x_pp_end_of_juvenile description	photoperiod	12.17	12.0	h
y_tt_floral_initiation units	TT from initiation to flowering	370.0	400 900	$^oCd^{-1}$
y_tt_flowering units	TT from flowering to start grain fill	300.0	24	$^oCd^{-1}$
y_tt_start_grain_fill units	Start grain fill to end grain fill	800.0	460 460	$^oCd^{-1}$
tt_maturity units	TT from maturity to harvest ripe	5.0	5.0	$^oCd^{-1}$

7.2.3.3 SoilN module

Parameters influencing soil fertility are mainly represented in the APSIM-SoilN module. Initial state variables (NO_3-N, NH_4-N, soil organic carbon, pH and C:N ratio for soil) were measured for each soil layer from the experimental site and used to parameterise APSIM-SoilN module. In the module, part of soil organic matter that is considered to be non-susceptible to microbial decomposition over the growing season is specified as 'finert' which typically will increase with depth. 'fbiom' specifies the initial BIOM pool as a fraction of the non-inert soil organic matter which more labile soil microbial biomass and microbial products (Table 7.3). Fbiom and Finert values were defined by fitting the measured and simulated OC. SoilN module was calibrated using values of NO_3-N, NH_4-N and soil organic carbon obtained from field experiment during the rice growth period in wet and dry seasons of 2007-2008.

Table 7.3 Soil Bulk density (BD), saturation (sat), lower limit of plant-available water (LL15), drained upper limit of water (DUL), organic carbon (OC), fraction of active soil organic material as microbial biomass (FBiom) and fraction of inert organic matter (Finert) at various soil depths for initiation of the APSIM model.

Depth (cm)	**BD** (g cm^{-3})	**Sat**	**DUL** (mm/mm)	**LL15**	**MWcon** (0-1)	**KS** mm/d	**OC** (%)	**F biom**	**F inert**
0-20	1.19	0.55	0.35	0.21	1	20	1.5	0.04	0.4
20-40	1.23	0.53	0.34	0.2	0	10.4	0.8	0.02	0.6
40-70	1.27	0.51	0.29	0.19	1	100	0.09	0.02	0.8
70-100	1.35	0.49	0.28	0.2	1	100	0.07	0.01	1.0

Fbiom and Finert values are default values from the APSIM model. Mwcon is calibrated values of drainage rate of each soil layer; a value of 0 indicates the layer is considered more impermeable to cascading flow. KS is calibrated value of saturated conductivity.

7.2.3.4 SoilWat modules

The soilWat module was parameterised using data from the field experiment includes soil bulk density, saturated water content, drained upper limit water content at field capacity (DUL) and crop lower limit (Table 7.3), and two parameters, U and CONA, which determine first and second stage soil evaporation coefficients. The later parameters were set at 6 mm and 3 mm day^{-1} respectively where the values accepted for tropical conditions such as those described here. After a rainfall event, a proportion of water in excess of field capacity that drains within a day was specified through a coefficient called SWCON, which was varied depending on soil texture. Poorly draining clay soils will characteristically have values <0.5 while sandy soils that have high water conductivity can have values >0.8. Soil water content measurements before sowing defined the initial soil water content of the soil (Table 7.3). The soil percolation rate was first estimated from daily observations on field water depths, and then fine-tuned by model fitting. Refining the parameter value was done when simulated field-water depths and infiltration rate best agreed with measured field-water depths.

7.2.3.5 Pond modules

Pond module was calibrated using the field experiment for daily water depth during the rice growth period in wet and dry seasons in 2007-2008. The dynamics of daily ponding depth was first estimated from daily observations of field water depths, and then fine-tuned by model fitting. Model parameters were further refined by trial and error until the simulated daily ponding depths best agreed with measured ponding depths (Table 7.3). A similar method was used for the calibration of NO_3-N, NH_4-N, temperature and pH of ponding water.

7.2.4 Model validation

The calibrated APSIM-Oryza model was validated using field experimental data from the rice-rice-legume crops sequence in 2008-2009. The details of methodology of the experiment are presented in Chapter 3 and brief description of methodology is presented in section 7.2.1 in this chapter.

7.2.5 Data analysis

The performance of the APSIM-Oryza model was evaluated using the absolute root mean square error ($RMSE_a$) and normalised root mean square error ($RMSE_n$) (Mayer and Butler, 1993; Yang et al., 2000; Bouman and van Laar, 2006; Zhang et al., 2007). Simulated and measured values of parameters were also graphically compared. The student's t test of means assuming unequal variance p(t) and linear regression analysis were also used to assess the goodness-of-fit between the measured and simulated results using the Genstat software (Version 9.2.0.153, VSN International Ltd, Oxford, 2008). The values of slope (α), intercept (β), and determination coefficient (R^2) of the linear regression between simulated and measured values were also calculated. If the p(t) was greater than 0.05, it was concluded that no significant differences between measured and simulated values was existed. A model also reproduces experimental data best when α is equal to 1, β is equal to 0, R^2 is equal to 1 and absolute $RMSE_a$ is similar to SD (Bouman and van Laar, 2006). Another statistical analysis used to evaluate the performance of the model in this study was efficiency of forecasting (EF) which has been used extensively in this type of study (Loague and Green, 1991). The value of EF represents the overall goodness-of-fit of the data with negative values indicating poor performance of the model, and values close to one representing high performance (Mayer and Butler, 1993).

$$\mathrm{RMSE_a} = \left(\frac{1}{n} \sum (S_i - M_i)^2 \right)^{0.5} \tag{7.2}$$

$$\mathrm{RMSE_n} = \frac{100 \left(\frac{1}{n} \sum (S_i - M_i)^2 \right)^{0.5}}{\overline{M}} \tag{7.3}$$

$$\mathrm{EF} = 1 - \frac{\sum (M_i - S_i)^2}{\sum (M_i - \overline{M})^2} \tag{7.4}$$

where n is number of observations; M_i and S_i are measured and simulated values, respectively. $\overline{M}$ is the mean of all measured values. The variable M_i itself is a mean value over the three replicates of the field experiments, which has a standard deviation associated with it. Mostly in model evaluation, any difference between simulated and measured values is attributed to model errors, whereas the variation in the measured value is not taken into account (Kobayashi and Salam, 2000; Gauch et al., 2003).

7.3 Results

7.3.1 Model calibration

The APSIM-Oryza model was calibrated using experimental data of rice-rice-legume crop sequences in 2007-2008. The performance of the model simulating the soil, crops and pond dynamics are presented below.

7.3.1.1 Floodwater dynamics during rice growth period

Simulated and measured daily water depth during rice growth period in wet-season of 2007/2008 and dry-season of 2008 for continuously submerged (CS) and alternately submerged and non-submerged (ASNS) irrigation treatments are graphically presented in Fig. 7. 1. In both wet and dry seasons for CS treatment, the dynamics of simulated daily ponded depth closely followed measured values at most level of ponded depth, ranging from 0 to 100 mm. Ponded depth at the beginning of rice growth was kept at 0-20 mm for 7 days after transplanting (DAT). However, APSIM-Oryza simulation produced 0 mm during this period. Floodwater was drained 10 days before rice harvested and ponded depth was zero during this period. APSIM simulation was able to reproduce similar results with measured values in this period. In ASNS irrigation treatment, simulated values generally followed the pattern of measured values. However, the performance of simulated daily ponded depth in the ASNS irrigation treatment was weaker than that in the CS irrigation treatment compared with measured values in both wet- and dry- seasons. Nevertheless, when water depth was below soil surface during nonsubmergence periods of rice growth, the model was unable to simulate the water depth in this case.

Goodness-of-fit parameters for water depth during calibration period were used to statistically define the performance of the model. Table 7.4 shows the goodness-of-fit parameters of water depth during rice growth periods for CS and ASNS irrigation treatments in wet-season of 2007/2008 and dry-season of 2008. For CS treatment in both wet- and dry-seasons, the values of student's t-test were 0.56 and 0.50 in the wet- and dry-seasons, respectively. This indicates that all simulated values are not significantly different with measured values at 95% confidence level. The values of slope (α) for both 2007/2008 and 2008 seasons (0.81 and 0.74, respectively) were close to one, although the intercept of linear relation between measured and simulated values (β) was higher than zero, which indicates the general overestimation of simulated values. Coefficients of determination (R^2) are all significant, although their values were low, indicating the scattered of the data as shown in Fig.7.1. The mean values of simulated ponded depth were close to the mean values of measured data with the simulated values being 5.27 % and 6.84 % higher in wet-season 2007/2008 and early dry-season 2008, respectively. Standard deviations (SD) of simulated values were similar to measured values. This indicates that the simulated values were in strong agreement with measured values (Jones and Kiniry, 1986). Furthermore, the EF value was 0.61 and 0.52 for both wet-season of 2007/2008 and dry-season of 2008 respectively, indicating good performance of the model simulation. The RMSE of simulated ponded depth was lower than SD measured values in both wet- and dry-seasons.

In general, all of these indicators strongly suggest that the performance of the model was good for CS irrigation treatment in simulating the dynamics of ponded depth during rice growth periods of wet-season of 2007/2008 and dry-season of 2008 for calibration test. However, performance of the model in wet season of 2007/2008 was better than in dry season of 2008. The values of student's t-test, α and R^2 were higher in wet season of 2007/2008 than in dry season 2008 while β values were similar. In addition, absolute RMSE and normal RMSE% were also higher in wet season of 2007/2008 than in dry season of 2008.

Table 7.4 Statistical analysis of model simulation of daily water depth in wet-season of 2007/2008 and dry-season of 2008 of rice at various irrigation treatments for calibration data sets.

Indicator	CS		ASNS	
	2007/2008	2008	2007/2008	2008
N	90	90	90	90
X_m (SD)	55.38 (28)	40.78(27)	9.3 (26.9)	-4.62
X_s (SD)	58.3 (27.6)	43.57 (26.5)	20.8 (18.4)	15.95
P(t)	0.56*	0.5*	0.01	<0.01
α	0.81	0.74	0.3	0.03
β	13.1	13.5	17.32	16.1
R^2	0.66	0.58	0.2	0.05
$RMSE_a$	16.4	17.2	17.8	15.2
$RMSE_n$	28.9	42.3	191.5	63.4
EF	0.61	0.52	0.02	-0.59

N, number of measured/simulated data pairs; X_m, mean of measured values in each season; X_s, mean of simulated values in each season; (SD), standard deviation of whole population; P(t), significance of student's t-test; in a column P(t), * means simulated and measured values are not significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, determination coefficient between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

In contrast, goodness-of-fit parameters indicated that the performance of the model to simulate water depth in ASNS irrigation treatment was lower than that in CS irrigation treatment. The student's t-test values indicated that simulated and measured values were significantly different at 95% confidence level. Moreover, the values of α and R^2 were low although RMSE was lower than SD measured values. The simulated ponded depth for ASNS irrigation treatment in rice wet-season of

2007/2008 was better than simulated values in rice dry-season of 2008 as indicated by higher value of R^2 and positive value of EF. The simulated values in early period of rice growth were quite good for both wet- and dry-seasons of 2007/2008 and 2008 in ASNS irrigation treatment. However, when measured water depth reached below soil surface, the simulated values deviated from measured values.

Simulated and measured water input during the rice growth period for CS and ASNS irrigation treatments in 2007/2008 and 2008 seasons are presented in Table 7.5. Simulated water input varied during rice growth periods in CS and ASNS irrigation treatments for both seasons. In CS irrigation treatment, simulated irrigation input was close to measured values with the difference of 13.1% and 5.8% for 2007/2008 and 2008 seasons respectively. Moreover, the difference between simulated and measured in total water input (irrigation+rainfall) was smaller than in irrigation input with 6.7% and 5.2% for 2007/2008 and 2008 seasons respectively. In ASNS irrigation treatment, the performance of the model to simulate water input was similar to CS irrigation treatment. Total water input was 3.7% and 14.8% higher in simulated values than that measured values for 2007/1008 and 2008 seasons respectively. This indicates that the model generally reproduced total water input in similar to measured values, although simulated daily water depth was in less agreement with measured values in the ASNS irrigation treatment.

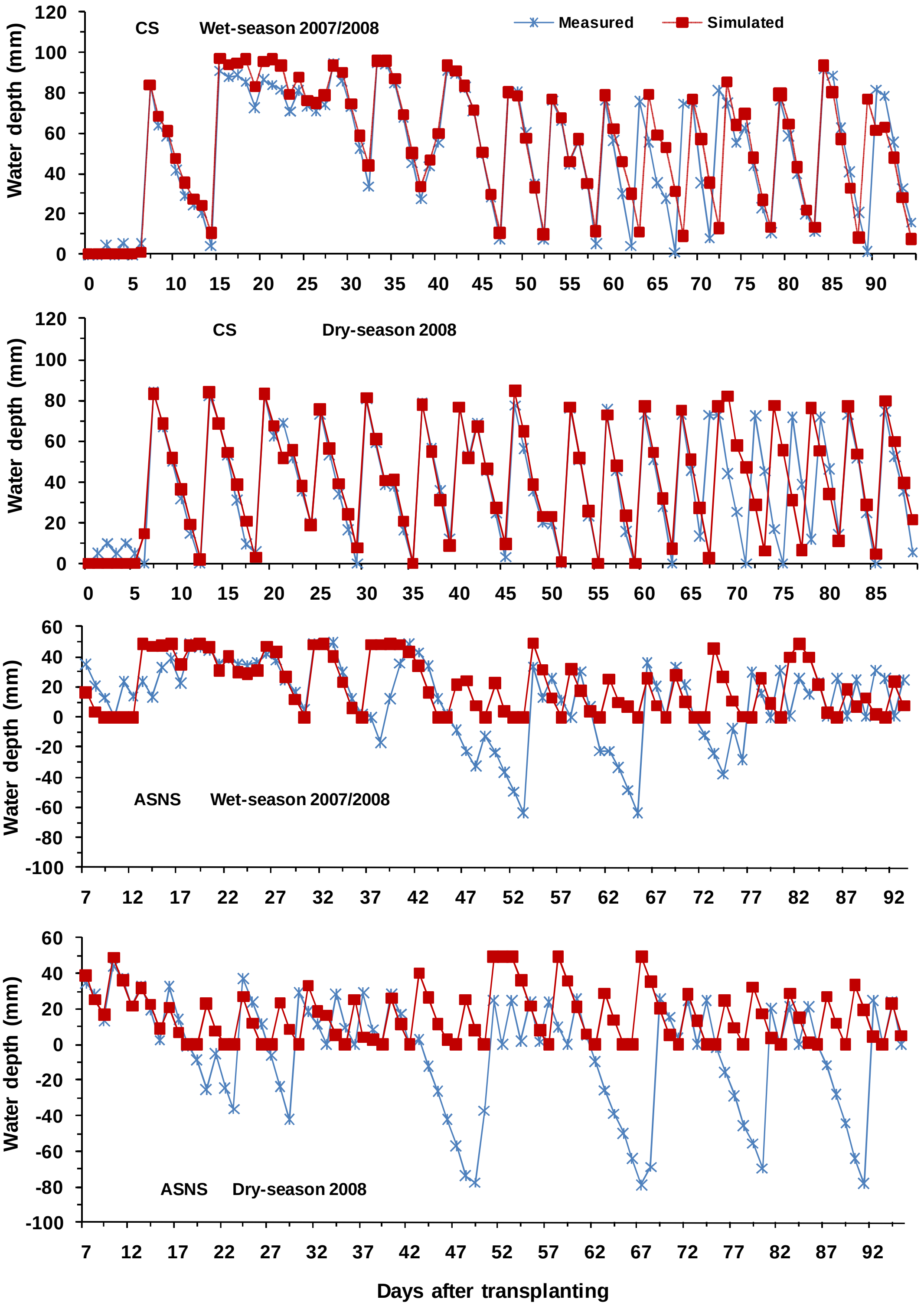

Figure 7.1 Simulated and measured daily water depth during rice growth period for continuously submerged (CS) and alternately submerged and non-submerged irrigation treatments in early wet-season of 2007/2008 and dry-season of 2008 for the calibration data sets. Negative value of water depth indicates presence of water level below soil surface.

Table 7.5 Measured and simulated water input during rice growth periods of 2007/2008 and 2008 seasons for calibration data set.

Seasons	Water input (mm)	CS				ASNS			
		Measured	Simulated	Difference		Measured	Simulated	Difference	
		(M)	(S)	(M-S)	(%)	(M)	(S)	(M-S)	(%)
2007/2008	Irrigation	1080.3	938.4	142.0	13.1	690.0	750	-59.6	-8.6
	Rainfall	1046	1046	0.0	0.0	940.0	940	0	0.0
	Total water input	2126.3	1984.4	142.0	6.7	1630.4	1690.0	-59.6	-3.7
2008	Irrigation	1820.4	1714	106.4	5.8	1102.0	1300	-197.8	-17.9
	Rainfall	233	233	0.0	0.0	233.0	233	0	0.0
	Total water input	2053.4	1947.0	106.4	5.2	1335.2	1533.0	-197.8	-14.8

7.3.1.2 pH and temperature of floodwater

Figure 7.2 shows the dynamics of pH and temperature during rice growth periods. pH and temperature were measured one day before and for ten days after the application of N fertiliser. In general, pH increased slightly to about 8 after the application of N fertiliser, then reducing to between 6.5 and 7. The reduction was more prominent during the 2008/2009 season. Denitrification of N mostly occur around pH=7 to 7.5, and almost ceases for pH<4 or pH>10 (Heinen, 2006). The simulated values were generally close to the measured values. Temperature of floodwater was around 25°C and it tended to decrease with time. The data of temperature during 2008-2009 rice growth periods were not complete as the temperature equipment was out of order. In general, simulated values was higher than the measured values particularly during 2007/2008 season.

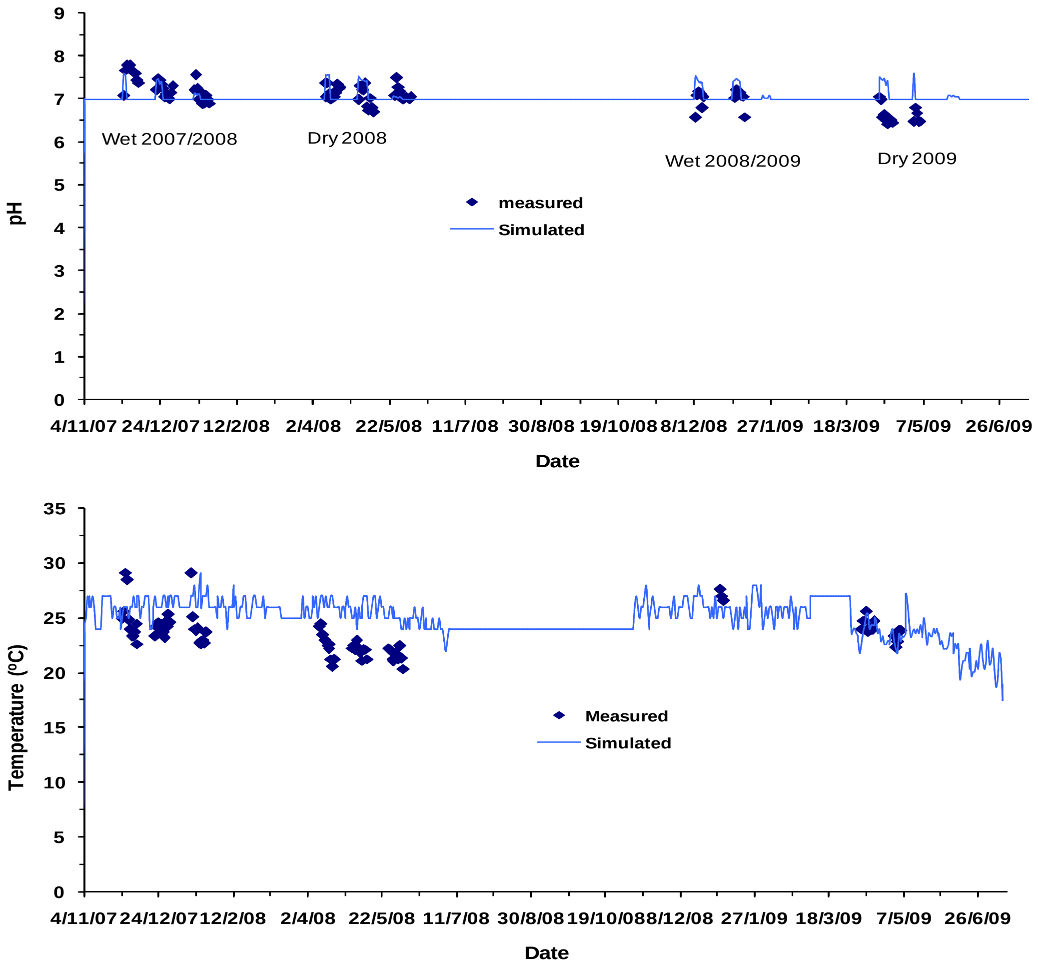

Figure 7.2 Simulated and measured pH and temperature during rice growth periods.

7.3.1.3 Soil organic carbon (OC) dynamics

Figure 7.3 shows the dynamics of soil OC during crop growth periods of rice-rice-legume crops sequence in 2007-2008. Since there was no statistically difference in soil organic carbon between irrigation treatments (CS and ASNS) and fertiliser rates during the whole crop sequence of 2007/2008, the values of measured soil OC were pooled together for goodness-of-fit parameters analysis and compared with simulated soil OC (see Chapter 5 section 5.3 and Chapter 6 section 6.3). In general, measured values of OC were more scattered than simulated values, indicating the dynamics change of organic carbon thorough crop sequence, although their variation were not significantly different. Measured OC values decreased with increased soil depth and simulated OC values followed the trend of measured values.

Table 7.6 shows the goodness-of-fit parameter of OC at different soil layers during crop growth periods of rice-rice-legume crops sequences in 2007-2008. Analysis of student's t-test showed that P(t) values were larger than 0.05, indicating that all simulated values are statistically similar to measured values except soil at layer 2 which is highly significant. The β values were generally close to zero indicating good agreement between simulated and measured values except for layer 1. The α value was small which indicates the general underestimation of simulated values and coefficients of determination (R^2) were low. Mean and SD of simulated values were lower than measured values in all soil layers. SD of simulated values decreased with increase in soil depth and SD values at layers 3 and 4 were zero, meaning that the layers have a single constant value. This indicates that no or very slow decomposition of organic carbon in a deeper soil layers in the model, while the decomposition processes existed in field although it was slow with measured values were more dispersed than simulated values as shown in Fig. 7.3. The EF values were small although these are greater than zero and the RMSE value was lower than SD measured values in all soil layers. In general, all of these indicators suggest that the performance of the model was quite good in simulating the dynamics of soil OC during crop growth periods of rice-rice-legume crops sequence in 2007-2008 for calibration test.

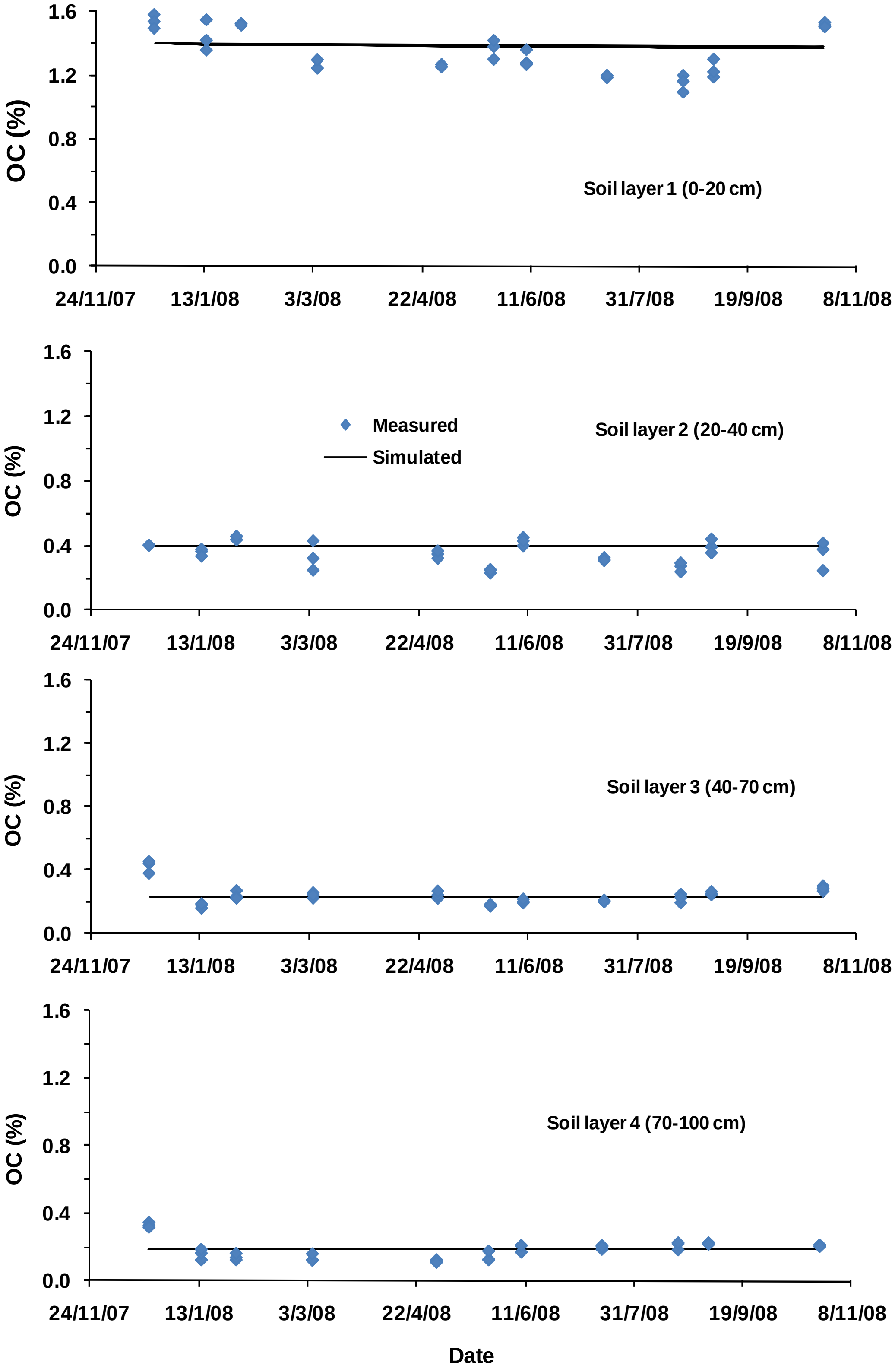

Figure 7.3 Simulated and measured soil organic carbon at different soil layers during crop growth periods in whole year of rice-rice-legume crops sequence of 2007-2008.

Table 7.6 Goodness-of-fit parameter of model simulation of organic carbon (OC) in rice-rice-legume crops sequence of 2007-2008 at different soil layers for calibration data sets.

Parameters		N	X_m (SD)	X_s (SD)	P(t)	α	β	R^2	$RMSE_a$	$RMSE_n$	EF
OC	Layer 1	48	1.346 (0.14)	1.383 (0.009)	0.145*	0.036	1.33	0.38	0.01	0.49	0.005
	Layer 2	48	0.351 (0.07)	0.397 (0.004)	0.001	0.009	0.39	0.63	0.002	0.62	0.42
	Layer 3	48	0.239 (0.07)	0.23 (0)	0.46*	-0.0006	0.23	0.08	0.0005	0.19	0.022
	Layer 4	48	0.188 (0.6)	0.19 (0)	0.788*	-9.00E-15	0.19	0.01	0.00	0.00	0.002

N, number of measured/simulated data pairs; X_m, mean of measured values in each season; X_s, mean of simulated values in each season; (SD), standard deviation of whole population; P(t), significance of paired t-test; in a column P(t), * means simulated and measured values are no significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, determination coefficient between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

7.3.1.4 Simulated and measured of ammonium-N concentration in soil

Simulated and measured ammonium-N (NH_4-N) concentration in soil at various soil layers and N fertiliser rates in continuously submerged (CS) irrigation treatment during crops growth periods in whole year of rice-rice-peanut crops sequence of 2007-2008 are presented in Fig. 7.4 and 7.5. In general, the trend in simulated soil NH_4-N followed the measured values although the measured values were higher than that the simulated values. Measured NH_4-N values increased with increased in N fertiliser application rates and decreased with increased in soil depth. Simulated NH_4-N concentration in soil also followed this pattern. Moreover, simulated values were close to zero at deeper soil depth during rice and legume crops growth periods suggesting that the simulated movement of NH_4-N through deeper soil layers was very slow compared with higher measured values. Simulated NH_4-N concentration in soil during aerobic period of the legume crops were also close to zero compared with higher measured values.

Figures 7.6 and 7.7 show the simulated and measured NH_4-N concentration in soil at various soil layers and N fertiliser rates in alternately submerged and non-submerged (ASNS) irrigation treatment during crops growth periods of rice-rice-soybean crops sequence of 2007-2008. The performance of the model to simulate NH_4-N dynamics during rice-rice-legume crops growth periods in ASNS irrigation treatment was similar to CS irrigation treatment. The ability of the model to simulate NH_4-N concentration in soil under various irrigation treatments and N fertiliser rates was assessed by comparing the simulated values with the measured data (Table 7.7). In all irrigation and N fertiliser variables, student's t-test values were highly significantly different, EF values were lower than zero, R^2 and α values were low, indicating that simulated values did not match with measured values although SD of measured values were higher than RMSE and β values were close to zero. These results suggests that there was a large discrepancy between simulated and measured NH_4-N concentration in soil at various soil layers and N fertiliser rates in both CS and ASNS irrigation treatments and that the performance of the model in this case was poor.

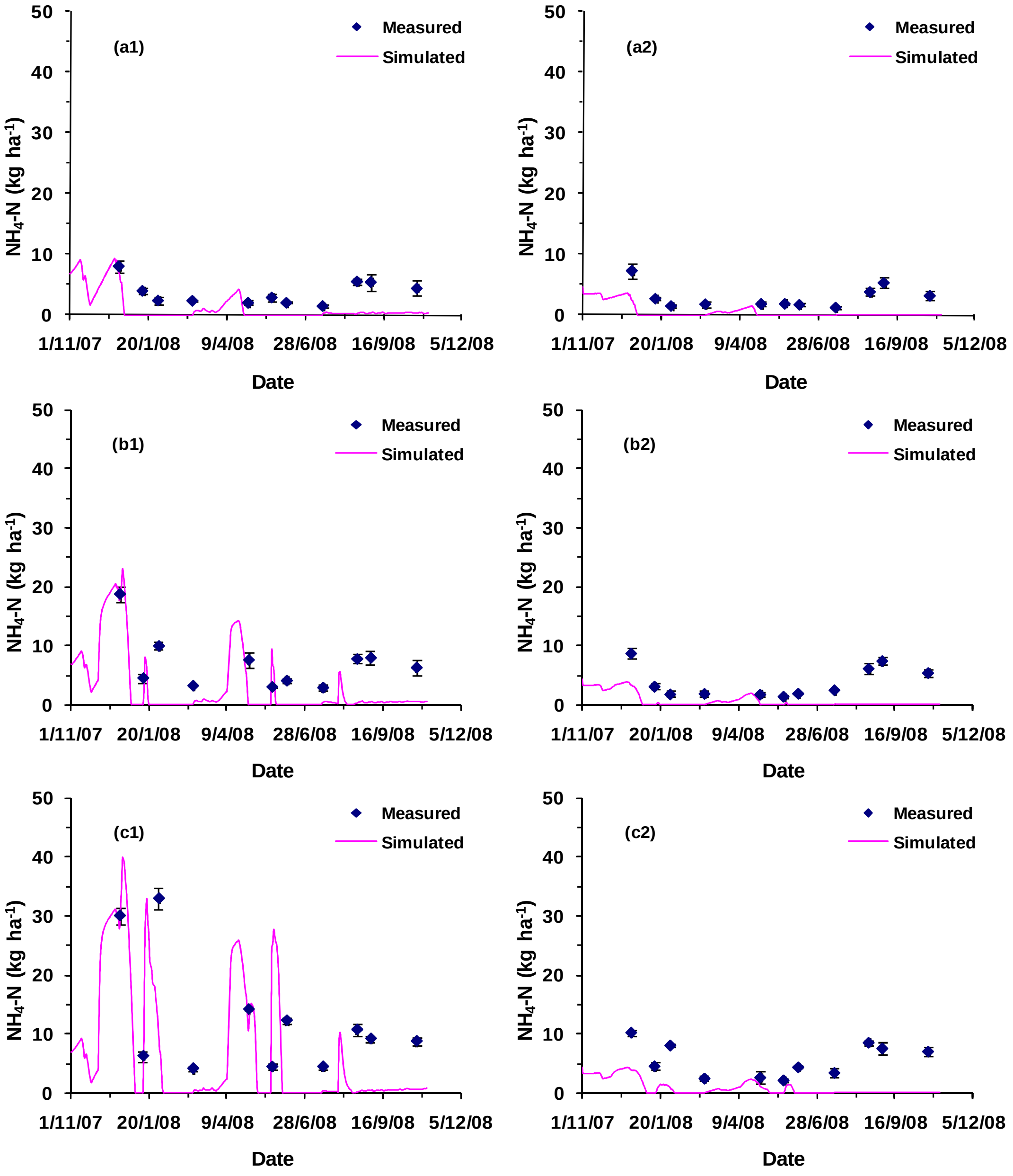

Figure 7.4 Simulated and measured NH_4-N concentration in soil at various soil layers (1 = 0-20 cm; 2 = 20-40 cm depth) and N fertiliser rates (a = 0 kg ha-1, b = 70 kg N ha-1 and c = 140 kg N ha^{-1}) in CS irrigation treatment during crop growth periods in whole year of rice-rice-peanut crops sequence of 2007-2008.

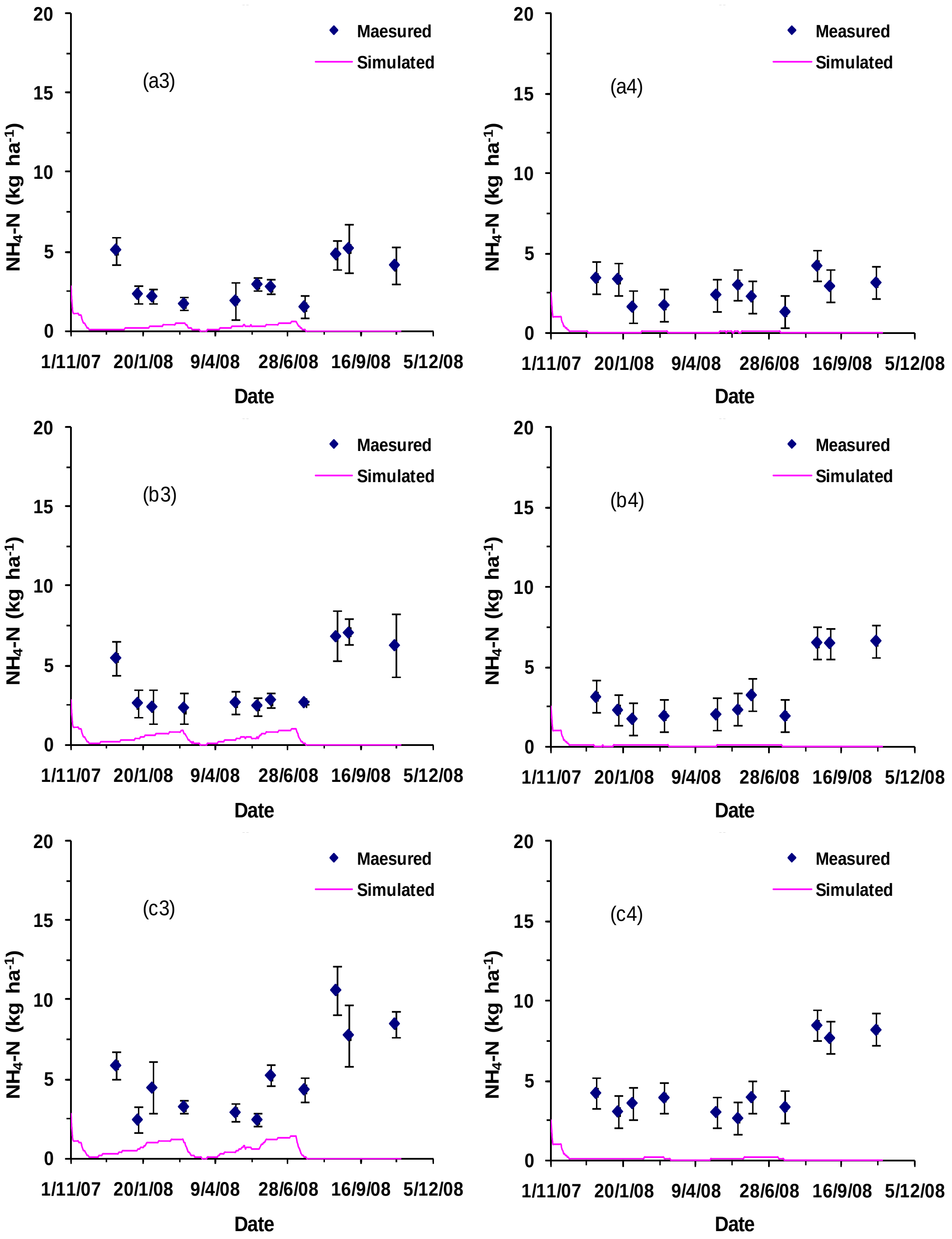

Figure 7.5 Simulated and measured NH_4-N concentration in soil at various soil depths (3 = 40-70 cm; 4 = 70-100 cm depth) and N fertiliser rates (a = 0 kg ha^{-1}, b = 70 kg N ha^{-1} and c = 140 kg N ha^{-1}) in CS irrigation treatment during crop growth periods in whole year of rice-rice-peanut crops sequence of 2007-2008.

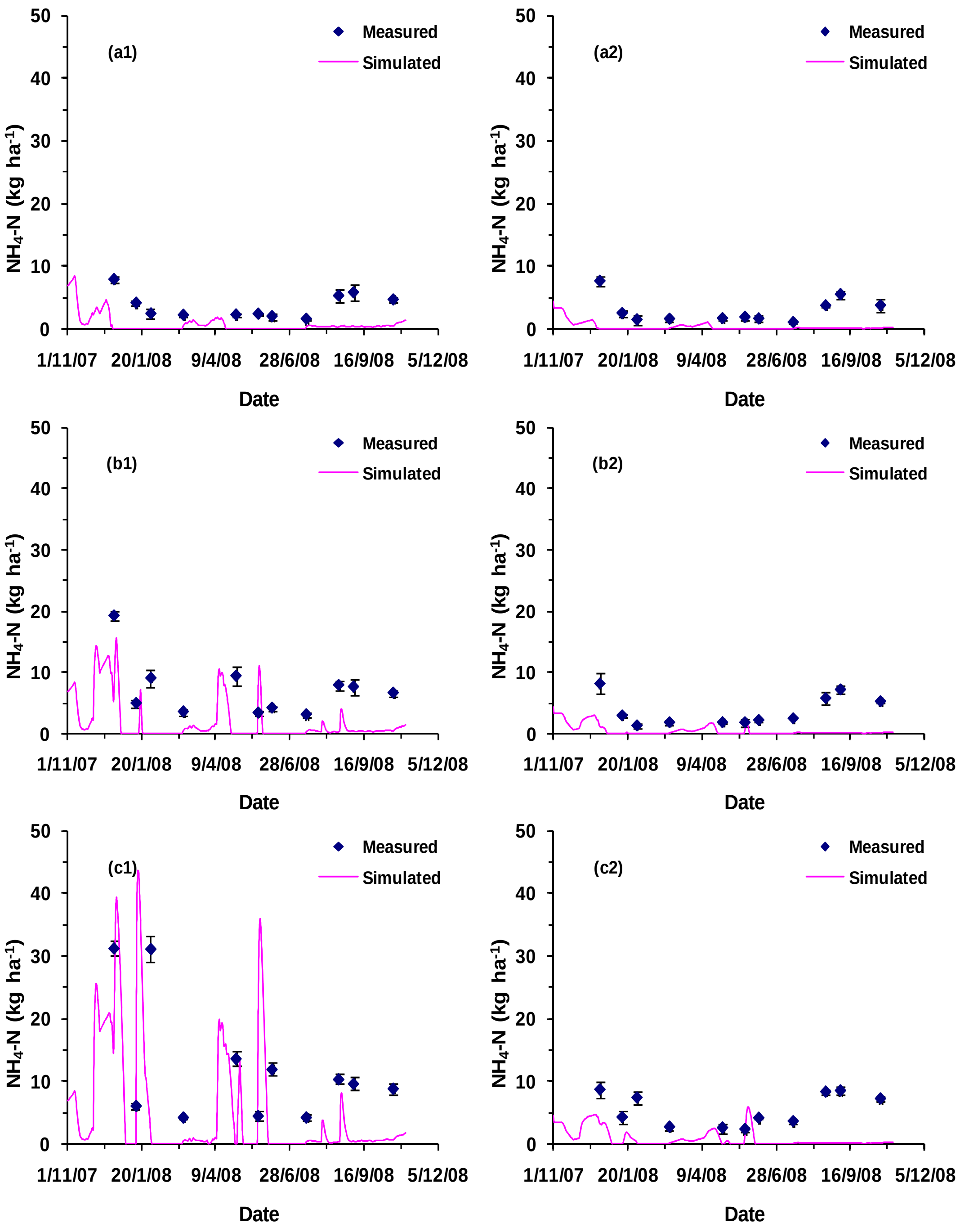

Figure 7.6 Simulated and measured NH_4-N concentration in soil at various soil layers (1 = 0-20 cm; 2 = 20-40 cm depth) and N fertiliser rates (a = 0 kg ha^{-1}, b = 70 kg N ha^{-1} and c = 140 kg N ha^{-1}) in ASNS irrigation treatment during crop growth periods in whole year of rice-rice-soybean crops sequence of 2007-2008.

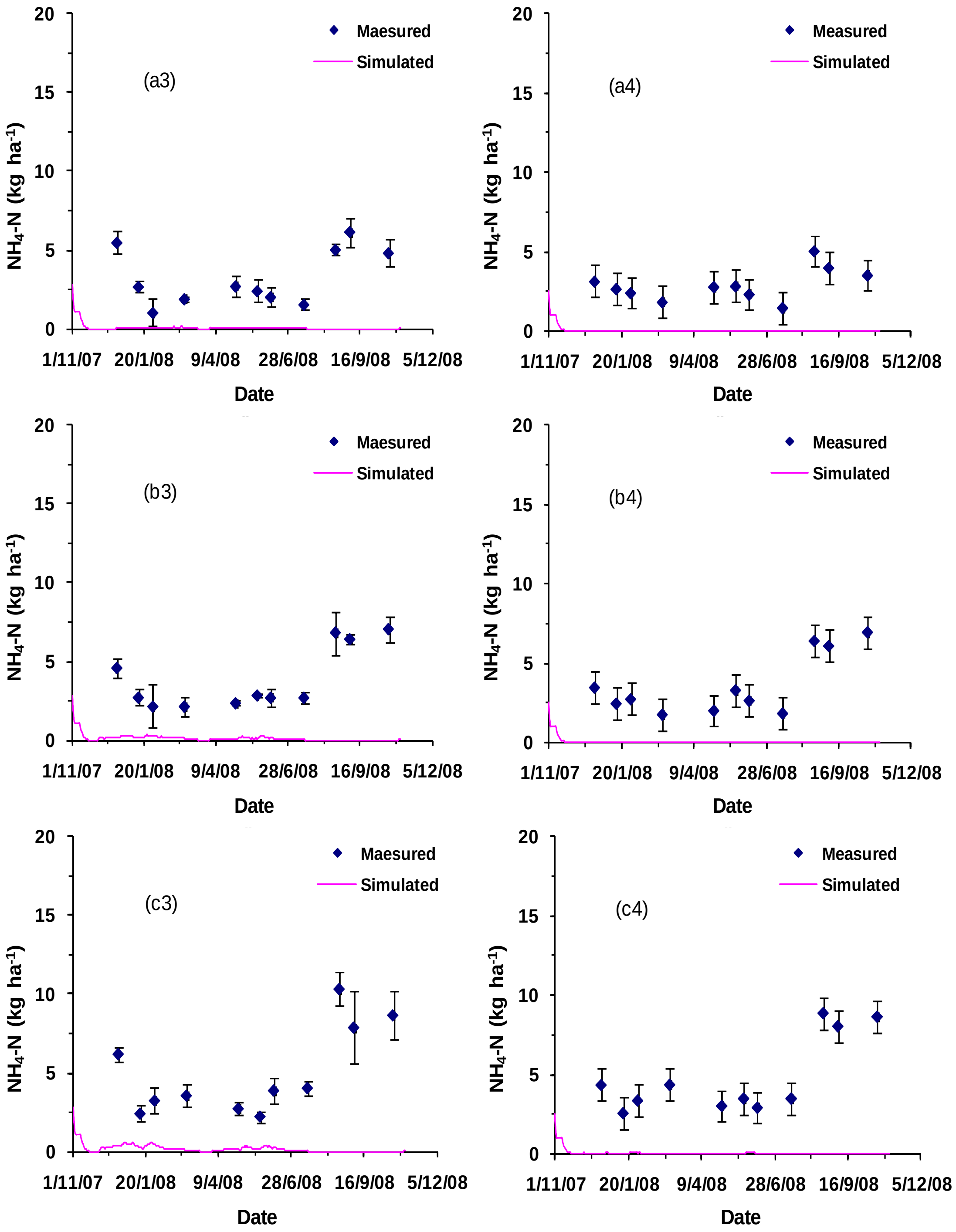

Figure 7.7 Simulated and measured NH_4-N concentration in soil at various soil depths (3 = 40-70 cm; 4 = 70-100 cm depth) and N fertiliser rates (a = 0 kg ha^{-1}, b = 70 kg N ha^{-1} and c = 140 kg N ha^{-1}) in ASNS irrigation treatment during crop growth periods in whole year of rice-rice-soybean crops sequence of 2007-2008.

Table 7.7 Statistical analysis of model simulation of ammonium-N (NH_4-N) concentration in soil at various irrigation treatments and N fertiliser rates in rice-rice-legume crops sequence of 2007-2008 for calibration data sets.

Variable	N	X_m (SD)	X_s (SD)	P(t)	α	β	R^2	$RMSE_a$	$RMSE_n$	EF
CS	132	4.92 (4.39)	0.55 (2.4)	<0.001	0.19	-0.37	0.12	2.28	46.36	-0.92
ASNS	132	4.92 (4.37)	0.55 (2.42)	<0.001	0.2	-0.41	0.13	2.27	46.13	-0.92
F0	88	3.17 (1.66)	0.08 (0.18)	<0.001	0.02	0.03	0.02	0.17	5.5	-3.49
F1	88	4.61 (3.21)	0.45 (1.43)	<0.001	0.15	-0.26	0.12	1.35	29.23	-1.58
F2	88	6.98 (6.11)	1.12 (3.88)	<0.001	0.05	0.19	0.14	3.69	52.92	-0.94

CS, continuously submerged; ASNS, alternately submerged and non-submerged; F0, 0 kg N ha^{-1}; F1, 70 kg N ha^{-1}; F2, 140 kg N ha^{-1}; N, number of measured/simulated data pairs; X_m, mean of measured values in each season; X_s, mean of simulated values in each season; (SD), standard deviation of whole population; P(t), significance of paired t-test; in a column P(t), * means simulated and measured values are no significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, determination coefficient between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

7.3.1.5 Simulated and measured nitrate-N concentration in soil

Figures 7.8 and 7.9 show simulated and measured nitrate-N (NO_3-N) concentration in soil at various soil layers and N fertiliser rates for CS and Fig 7.10 and 7.11 for ASNS irrigation treatments during crops growth periods in whole year of rice-rice-legume crops sequence of 2007-2008. The model performance in simulating NO_3-N concentration in soil was similar to NH_4-N concentration in soil. The simulated NO_3-N concentration in soil was lower than that of measured values in all variables of irrigation and N fertiliser treatments. Measured NO_3-N concentration in soil increased as N fertiliser increased and as soil depth increased, indicating there was NO_3-N leaching occurring through deeper soil layers. The model could not simulate this condition where simulated values were zero for most of the time during rice growth periods except at break periods between rice wet and dry seasons, and between rice and legume crops seasons. During the legume crops season, simulated NO_3-N increased as N fertiliser rates increased because of nitrification during aerobic condition and decreased as soil depth increased in both CS and ASNS irrigation treatments. However, measured values were higher than simulated values. Table 7.8 shows statistical analysis of goodness-of-fit parameters of simulated NO_3-N concentration in soil under various irrigation treatments and N fertiliser rates. These analyses generally show that the simulated NO_3-N concentration in soil did not match with measured values, suggesting that there was a discrepancy between simulated and measured NO_3-N at various soil layers and N fertiliser rates in both CS and ASNS irrigation treatments. Simulated NO_3-N concentration in soil during legume crops growth periods was higher than during the rice growth periods although its values were lower than measured values.

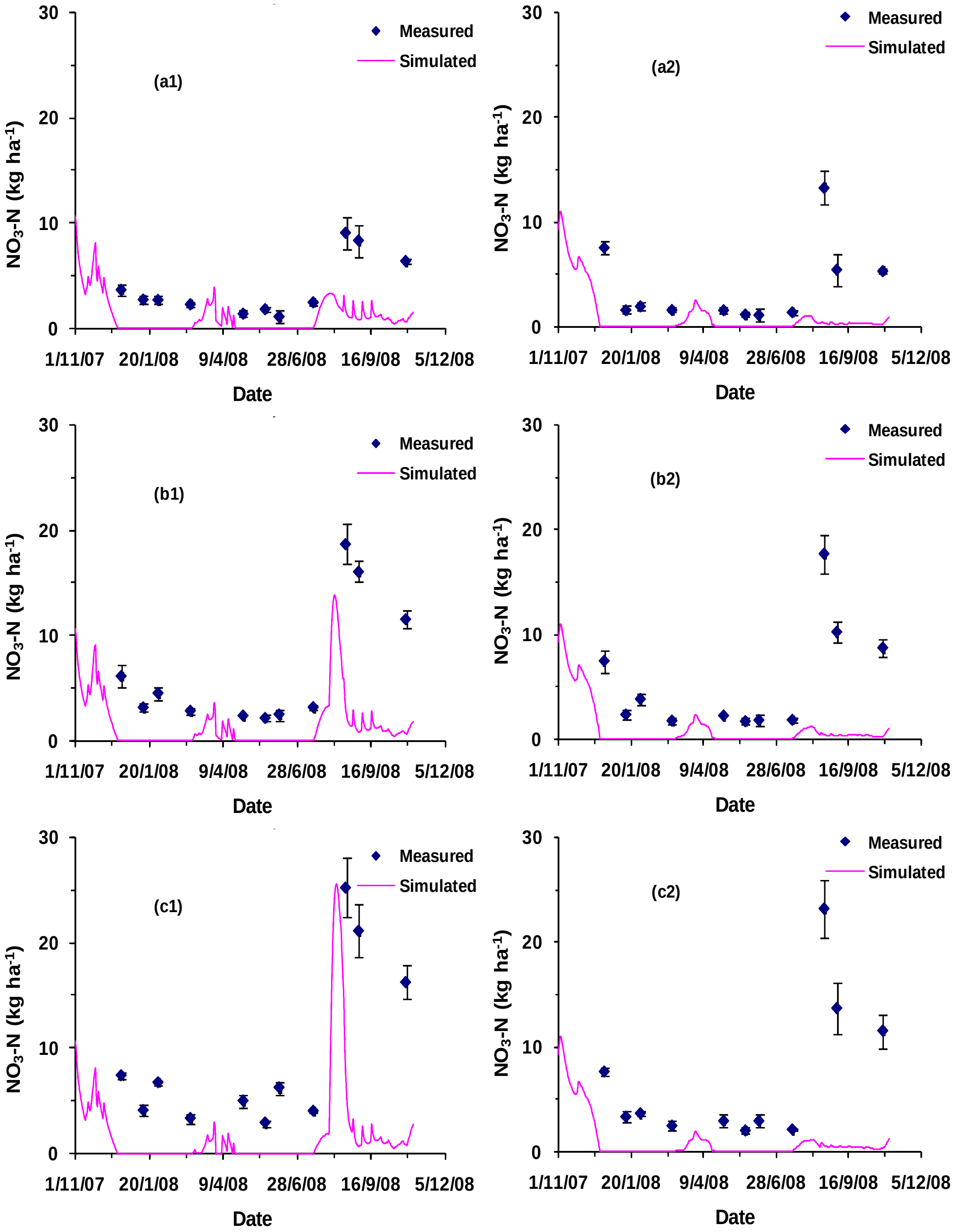

Figure 7.8 Simulated and measured NO_3-N concentration in soil at various soil layers (1 = 0-20 cm; 2 = 20-40 cm depth) and N fertiliser rates (a = 0 kg ha^{-1}, b = 70 kg N ha^{-1} and c = 140 kg N ha^{-1}) in CS irrigation treatment during crop growth periods in whole year of rice-rice-peanut crops sequence of 2007-2008.

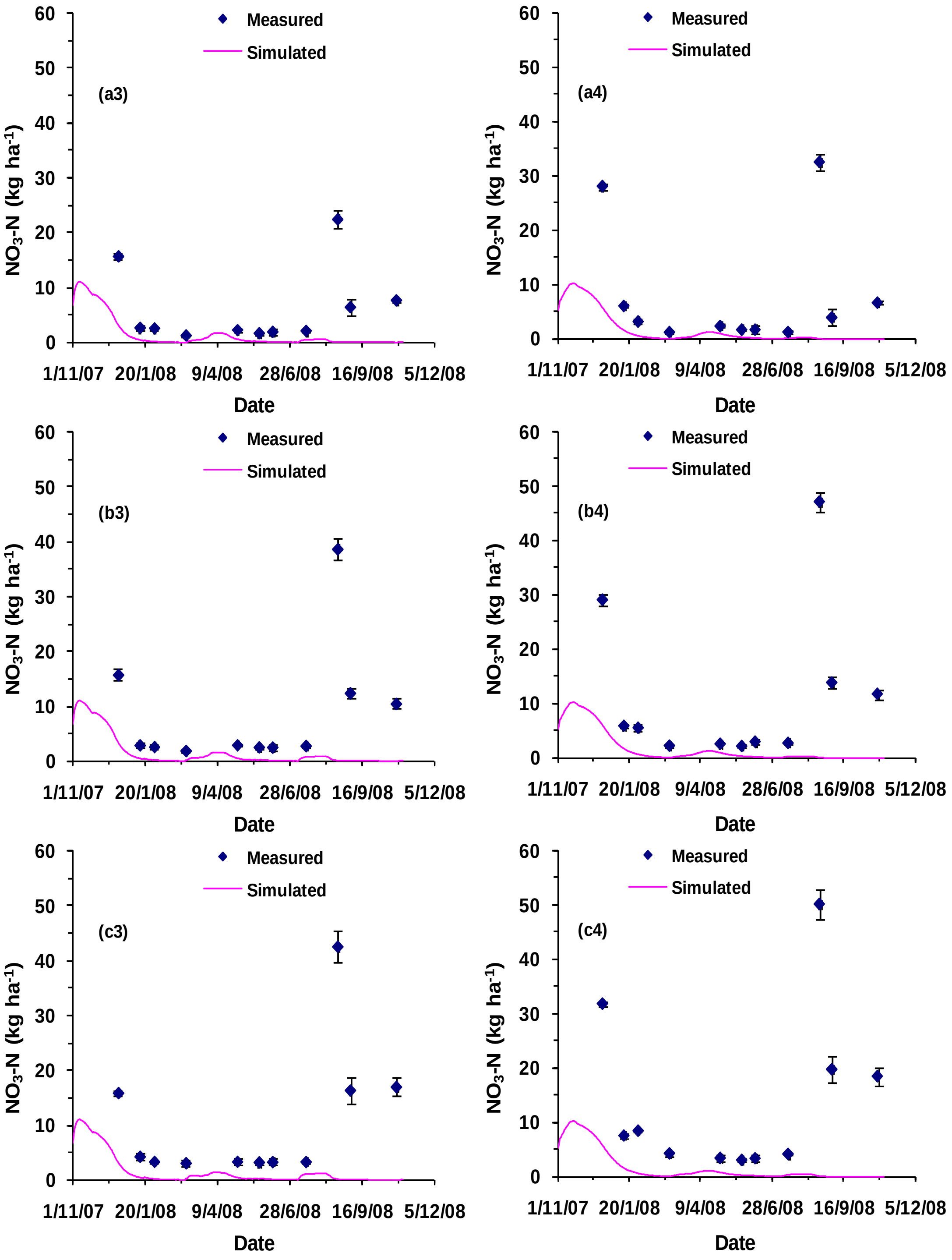

Figure 7.9 Simulated and measured NO_3-N concentration in soil at various soil depths (3 = 40-70 cm; 4 = 70-100 cm) and N fertiliser rates (a = 0 kg ha^{-1}, b = 70 kg N ha^{-1} and c = 140 kg N ha^{-1}) in CS irrigation treatment during crop growth periods in whole year of rice-rice-peanut crops sequence of 2007-2008.

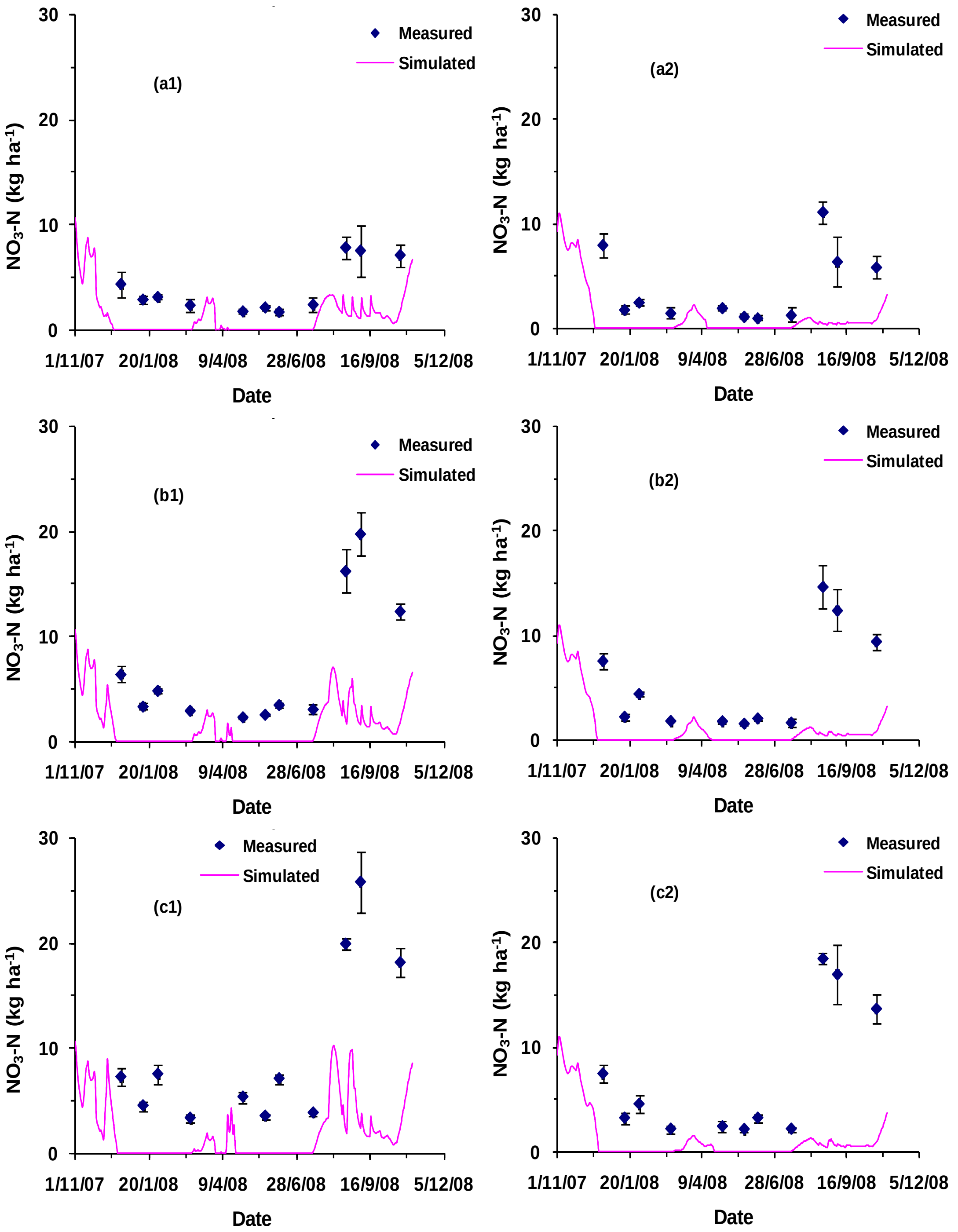

Figure 7.10 Simulated and measured NO$_3$-N concentration in soil at various soil layers (1 = 0-20 cm; 2 = 20-40 cm) and N fertiliser rates (a = 0 kg ha^{-1}, b = 70 kg N ha^{-1} and c = 140 kg N ha^{-1}) in ASNS irrigation treatment during crop growth periods in whole year of rice-rice-soybean crops sequence of 2007-2008.

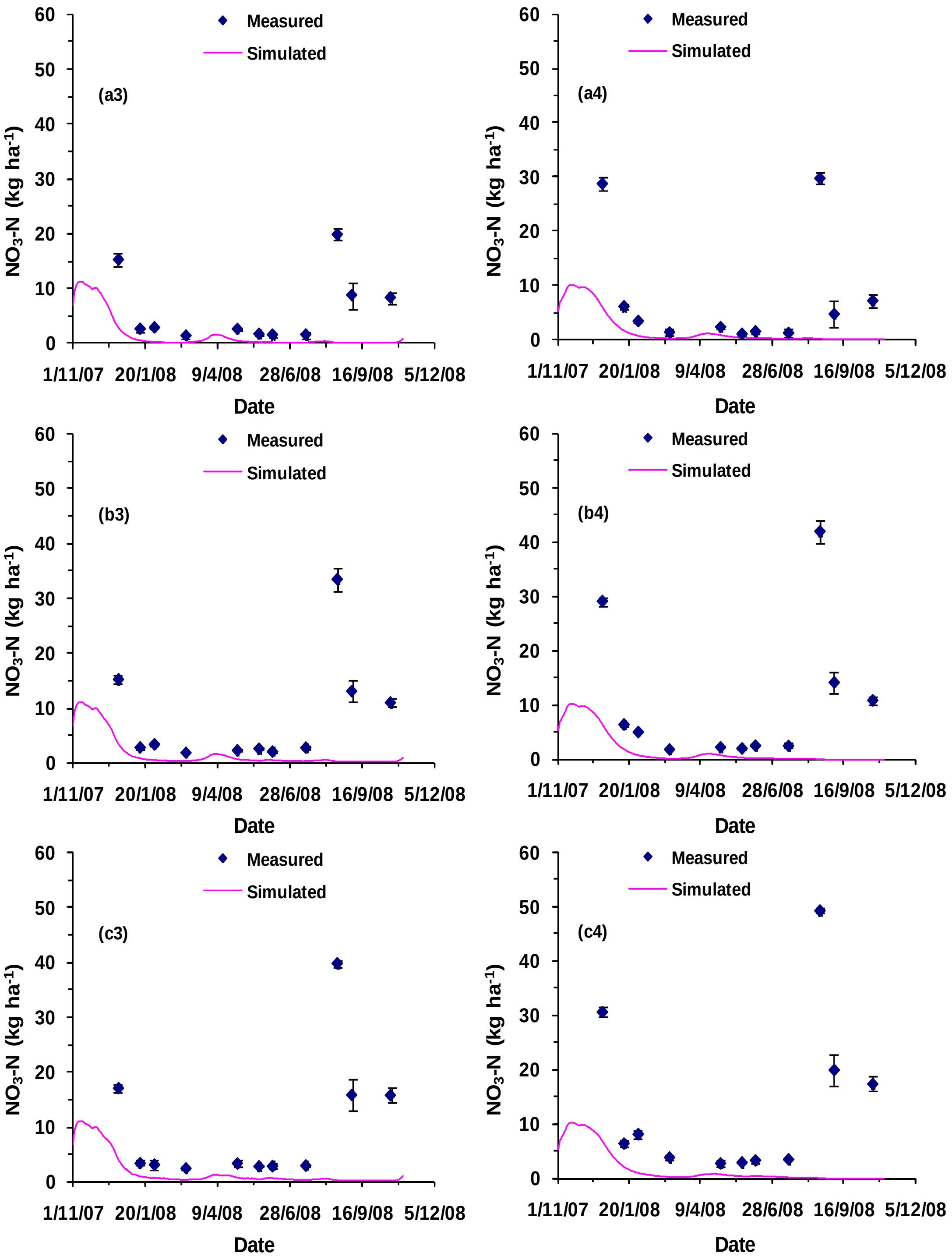

Figure 7.11 Simulated and measured NO_3-N concentration in soil at various soil depths (3 = 40-70 cm; 4 = 70-100 cm depth) and N fertiliser rates (a = 0 kg ha^{-1}, b = 70 kg N ha^{-1} and c = 140 kg N ha^{-1}) in ASNS irrigation treatment during crop growth periods in whole year of rice-rice-soybean crops sequence of 2007-2008.

Table 7.8 Statistical analysis of model simulation of nitrate-N (NO_3-N) concentration in soil at various irrigation treatments and N fertiliser rates in rice-rice-legume crops sequence of 2007- 2008 for calibration data sets.

Variable	N	X_m (SD)	X_s (SD)	P(t)	α	β	R^2	$RMSE_a$	$RMSE_n$	EF
CS	132	7.88 (9.5)	0.53 (1.2)	<0.001	0.05	0.14	0.17	1.06	13.44	-0.52
ASNS	132	7.78 (9.0)	0.6 (1.2)	<0.001	0.06	0.14	0.2	1.08	13.92	-0.54
F0	88	5.44 (6.7)	0.48 (1.1)	<0.001	0.09	-0.01	0.32	0.88	16.25	-0.4
F1	88	7.79 (9.3)	0.56 (1.2)	<0.001	0.05	0.17	0.16	1.07	13.44	-0.55
F2	88	10.09 (10.7)	0.66 (1.3)	<0.001	0.05	0.19	0.14	1.22	12.05	-0.71

CS, continuously submerged; ASNS, alternately submerged and non-submerged; F0, 0 kg N ha^{-1}; F1, 70 kg N ha^{-1}; F2, 140 kg N ha^{-1}; N, number of measured/simulated data pairs; X_m, mean of measured values in each season; X_s, mean of simulated values in each season; (SD), standard deviation of whole population; P(t), significance of paired t-test; in a column P(t), * means simulated and measured values are no significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, determination coefficient between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

7.3.1.6 Biomass and yield

The dynamincs of the simulated and measured biomass variable at various of N fertiliser rates ranging from 0 to 140 kg ha^{-1} and irrigation management (CS and ASNS) in whole year of rice-rice-peanut and rice-rice-soybean crops sequences in 2007-2008 are presented in Fig 7.12 and Fig. 7.13 respectively. For statistical analysis, rice yields in all seasons were pooled together regardless of irrigation and N fertiliser treatments due to small sample size, while yield of peanut and soybean were analysed by simply comparing between measured and simulated values. The model starts simulating rice growth from emergence to harvest stage. Simulated growth development at transplating date was delayed (Fig. 7.12 and 7.13) because growth recovery during transplanting shock which causes a delay in phenological development (Bouman et al., 2001).

In the wet-season CS treatment, simulated biomass at different growth stages was very close to measured values at all levels of N fertiliser. In the dry-season, however, simulated biomass was higher than measured values at all levels of N fertiliser. The simulated biomass was close to measured values during tillering stage and exceeded measured biomass from panicle initiation onward at all levels of N fertiliser, although simulated biomass was closer to measured values at panicle initiation and flowering stages at 140 kg N ha^{-1}. However, these patterns were slightly different in ASNS irrigation treatment. In the wet-season ASNS treatment, the simulated biomass at all rice growth stages was close to measured values, except at harvesting stage at all levels of N fertiliser which was below measured values. Under-simulated values increased as N fertiliser increased at harversting stage. In the dry-season, however, simulated biomass during the growth period of rice was close to measured biomass at all levels of N fertiliser. The APSIM-Oryza was able to satisfactoraly simulate growth development of legume crops planted following the rice dry season of the rice-rice-legume crops sequence. Simulated biomass of peanut growth followed measured values closely at all levels of N fertiliserbut soybean biomass slightly over-estimated at productive stages for all levels of N fertiliser.

Figure 7.14 shows the comparison between measured and simulated yield of rice in the rice-rice-legume crop sequence in 2007-2008. In general, simulated yield matched the pattern of measured yield with slight over-prediction under both F2 and

F1 treatments and with slight under-prediction under F0 treatment. Coefficient of determination (R^2) was 0.70 which indicate the close agreement between measured and simulated values (Table 7.10).

Measured and simulated yield of peanut and soybean at different N fertiliser rates are presented in Table 7.9. The APSIM-Oryza was satisfactorily able to simulate yield of legume crops at all N fertiliser rates. Simulated peanut yields matched well with measured values while soybean yields slightly under-estimated at all levels of N fertiliser. This indicated better performance of the model in simulating peanut yield than soybean in this condition. The mean diference between simulated and measured yields of peanut and soybean regardless of N fertiliser rates were 1.63% and 17.26% respectively. Measured yield tended to decrease at the highest N fertiliser rate in both peanut and soybean crops. This pattern was also followed by the model where simulated yield decreased as N fertiliser rates increased.

Table 7.10 shows the goodness-of-fit parameters of biomass of rice at various irrigation managements, peanut and soybean biomass, and rice yield in the wet-season of 2007/2008 and the dry-season of 2008. The student's t-test values of biomass and yield for rice in both CS and ASNS irrigation treatments and legume crops indicate that all simulated values were not significantly different with measured values at 95% confidence level. The values of slope (α) were close to one although the intercept of linear relation between measured and simulated values (β) were higher than zero. Coefficient of determinations (R^2) is all significant with their values close to one which indicate the close agreement between measured and simulated values. The mean values of simulated biomass of rice were higher than mean of measured values by 18 % and 20 % different for CS and ASNS irrigation treatments respectively. Standard deviation (SD) of simulated biomass was close to measured values although their values were high which indicate the scatter of data. Furthermore, mean and SD of simulated legume crops were very close to measured values. These indicate that the simulated values were in good agreement with measured values in both CS and ASNS irrigation treatments of rice and legume crops. The EF value for rice biomass in CS and ASNS and legume crop biomass were close to one except for rice yield, indicating high performance of the model simulation. EF for rice yield was positive but low at 0.19. The RMSE of simulated biomass of rice and legume crops and yield of rice were lower than SD measured values. In general, all of these indicators suggest that the performance of the model is acceptable in simulating the dynamics of biomass and yield for rice in the CS and ASNS irrigation treatments and for legume crops biomass during the growth periods of the calibration test.

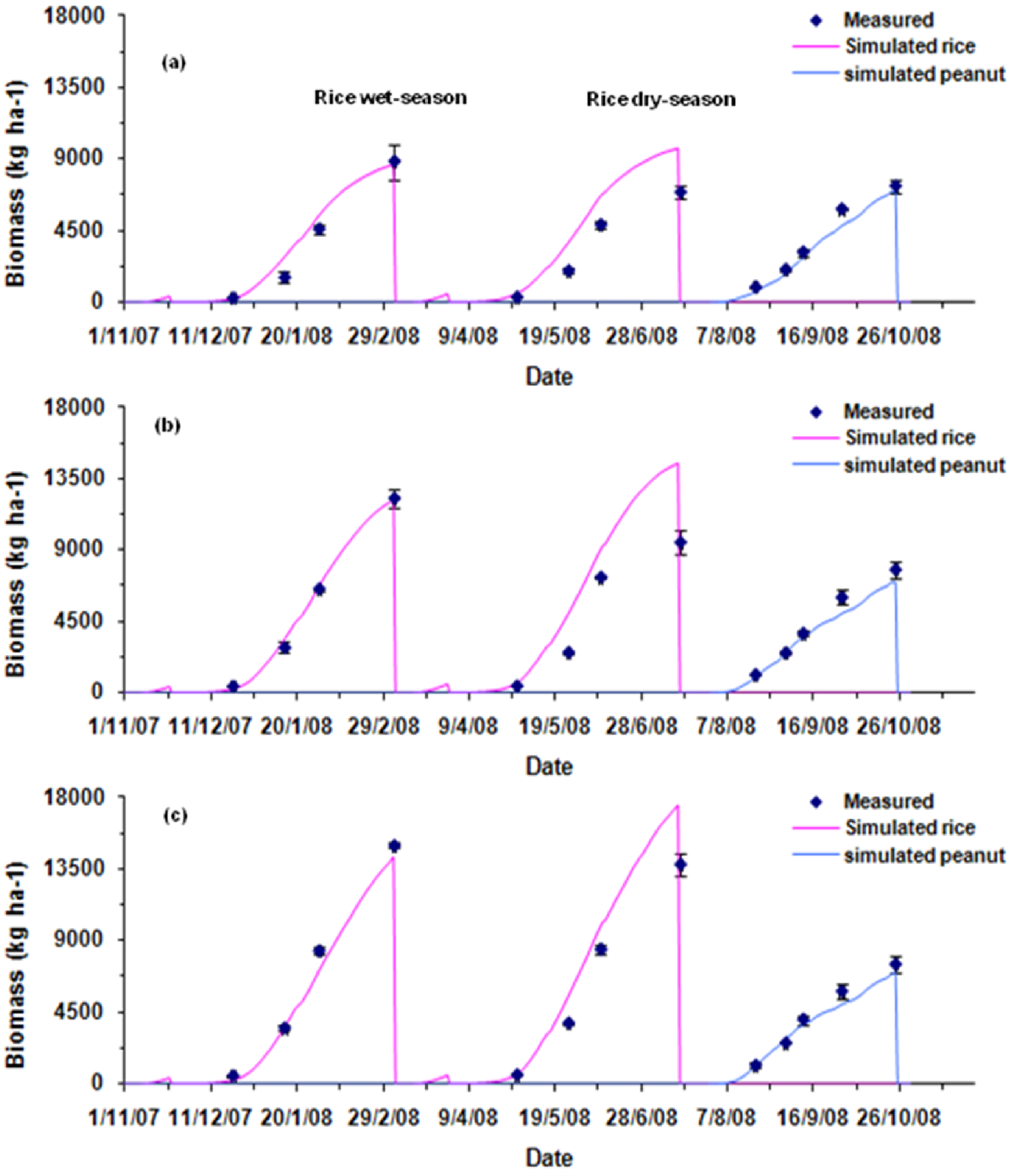

Figure 7.12 Simulated and measured total biomass of rice in CS irrigation treatment and peanut in whole year of rice-rice-peanut crops sequence at various urea fertiliser rates; (a) is 0 kg ha-1 for both rice and peanut crops; (b) is 70 and 12 kg N ha^{-1} for rice and peanut crop respectively; (c) is 140 and 24 kg N ha^{-1} for rice and peanut respectively.

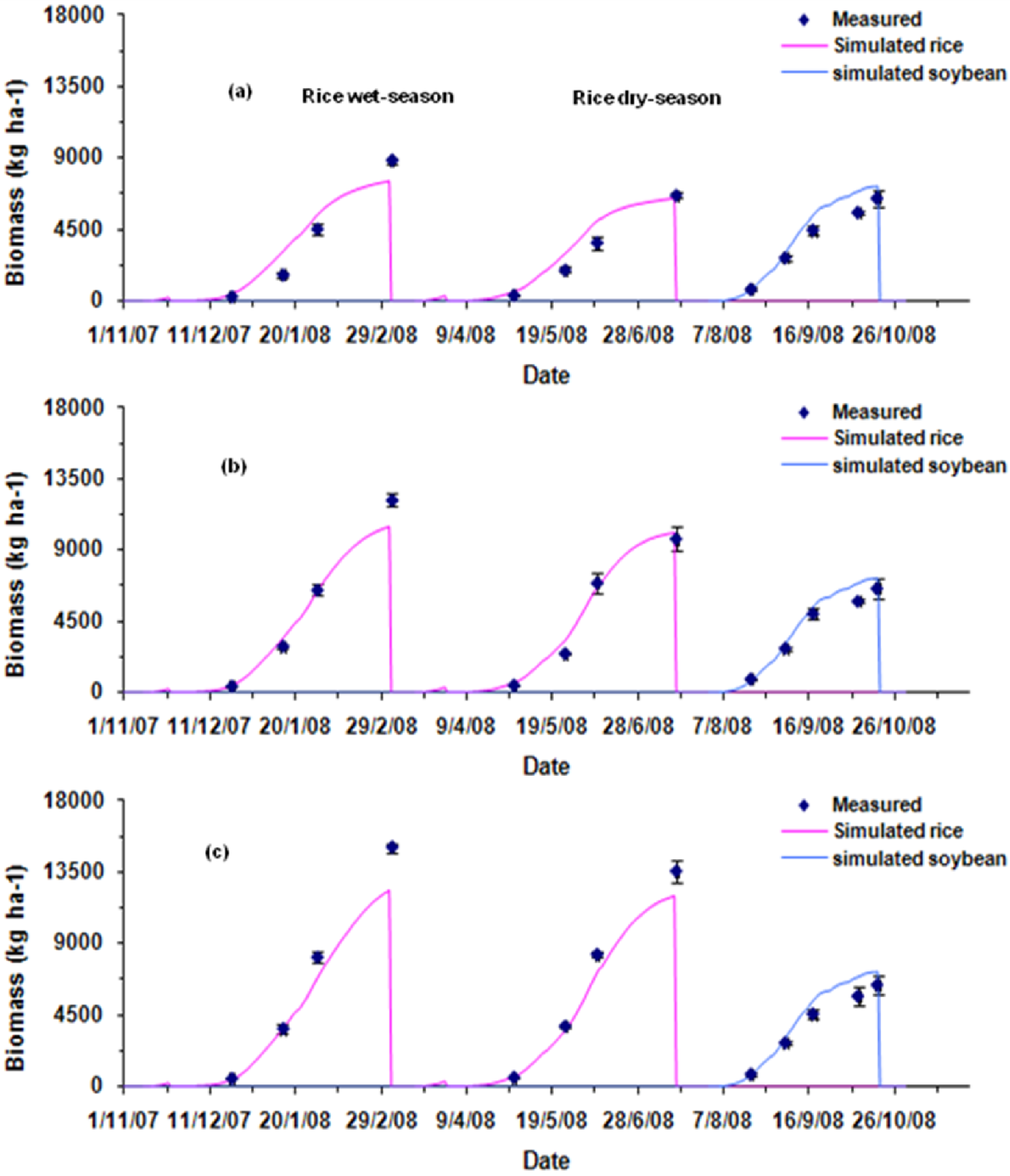

Figure 7.13 Simulated and measured total biomass of rice in ASNS irrigation treatment and soybean in whole year of rice-rice-soybean crops sequence at various N fertiliser rates; (a) is 0 kg ha^{-1} for both rice and soybean crops; (b) is 70 and 12 kg N ha $^{-1}$ for rice and soybean crops respectively; (c) is 140 and 24 kg N ha^{-1} for rice and soybean respectively.

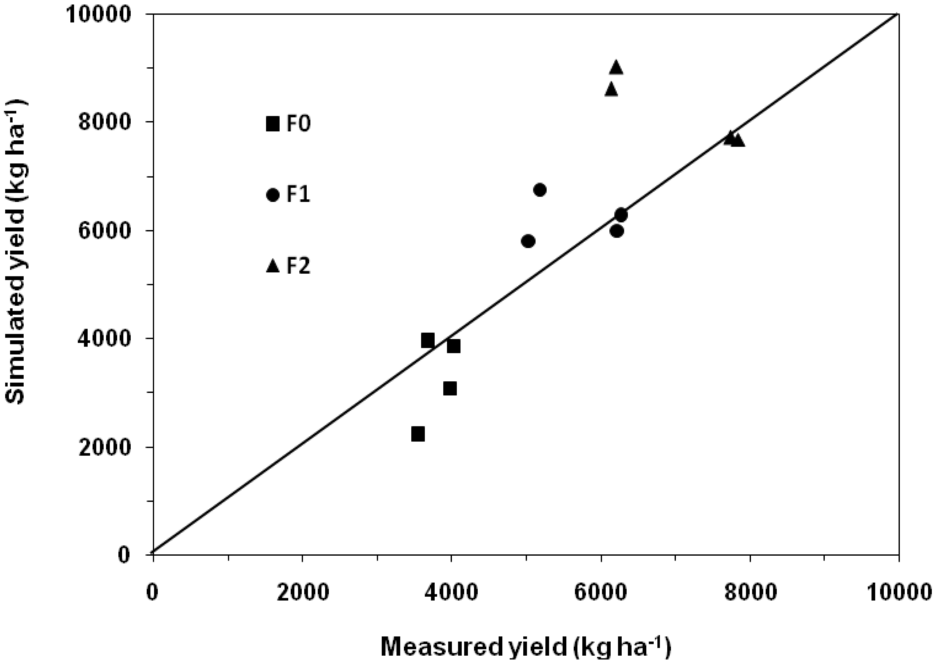

Figure 7.14 Simulated and measured yield of rice in whole year of rice-rice-legume crops sequence of 2007-2008 calibration data set solid line is 1:1 relationship.

Table 7.9 Measured and simulated yield of peanut and soybean at various N fertiliser rates in dry-season of 2008 for calibration data set. Values in brackets indicate standard deviation, n = 3).

Crops	N rates (kg ha^{-1})	Measured (M)	Simulated (S)	M-S	Difference (%)
Peanut	0	2077 (25)	2075.9	1.1	0.05
	12	2019 (38)	2076.4	-57.4	-2.84
	24	2010 (36)	2050.0	-40	-1.99
Soybean	0	2233 (113)	1968.8	264.2	11.83
	12	2361 (15)	1862.6	498.4	21.11
	24	2211 (125)	1794.5	416.5	18.84

Table 7.10 Statistical analysis of model simulation of biomass of rice, peanut and soybean, and rice yield in rice-rice-legume crops sequence of 2007-2008 for calibration data sets.

Variable	parameters	N	X_m (SD)	X_s (SD)	P(t)	α	β	R^2	$RMSE_a$	$RMSE_n$	EF
Rice-CS	Biomass	24	5202 (4472)	6151 (4058)	0.52*	1.06	590	0.91	1474	26.0	0.84
Rice-ASNS	Biomass	24	5119 (4439)	6165 (4936)	0.44*	1.06	754	0.94	1201	21.3	0.87
peanut	Biomass	15	4095 (2426)	3748 (2161)	0.68*	0.88	129	0.99	279	7.1	0.95
Soybean	Biomass	15	4067 (2132)	4021 (2243)	0.96*	1.04	-192	0.97	407	10.1	0.96
Rice	yield	12	5489 (1491)	5913 (2214)	0.59*	1.24	-897	0.70	1276	22.4	0.19

N, number of measured/simulated data pairs; X_m, mean of measured values in each season; X_s, mean of simulated values in each season; (SD), standard deviation of whole population; P(t), significance of paired t-test; in a column P(t), * means simulated and measured values are not significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, coefficient determination between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

7.3.1.7 Leaf area index (LAI) of rice and legume crops

Figures 7.15 and 7.16 show the dynamics of LAI of rice in the wet and dry seasons, and legume crops following dry season of rice at various N fertiliser rates for CS and ASNS irrigation treatments, respectively. In general, simulated LAI followed closely the pattern of measured values. In the wet season for both CS and ASNS irrigation treatments, simulated LAI followed closely measured values in early growth and at harvesting stages. However, simulated values were higher than measured values at flowering stage for zero N fertiliser, but this trend was reversed at higher N fertiliser rates. The simulated LAI patterns for rice in the dry season were similar to the wet season. Simulated LAI for peanut and soybean followed closely the pattern of measured values in all N fertiliser rates. It was not possible to measure the LAI for soybean at harvesting stage as all leaves were senescenced at harvest stage.

Table 7.11 shows the goodness-of-fit parameters of LAI for rice at various irrigation treatments and legume crops in rice-rice-legume crops sequence of 2007-2008. The t-test values of LAI for rice in both CS and ASNS irrigation treatments and legume crops indicate that simulated values statistically was similar to measured values at 95% confidence level. The values of α and R^2 were close to one, which indicate the close agreement between measured and simulated values and the values of β were higher than zero. The mean values and SD of simulated LAI were similar to the mean and SD of measured values in both CS and ASNS irrigation treatments and legume crops. These indicate that the simulated values were in close agreement with measured values in both CS and ASNS irrigation treatments and legume crops. Furthermore, the EF value for CS and ASNS and legume crops were close to one, indicating high performance of the model simulation. The RMSE of simulated LAI for rice and legume crops were lower than SD measured values. In general, all of these statistical indicators suggest that the performance of the model is acceptable in simulating the dynamics of LAI for rice in the CS and ASNS irrigation treatments and legume crops.

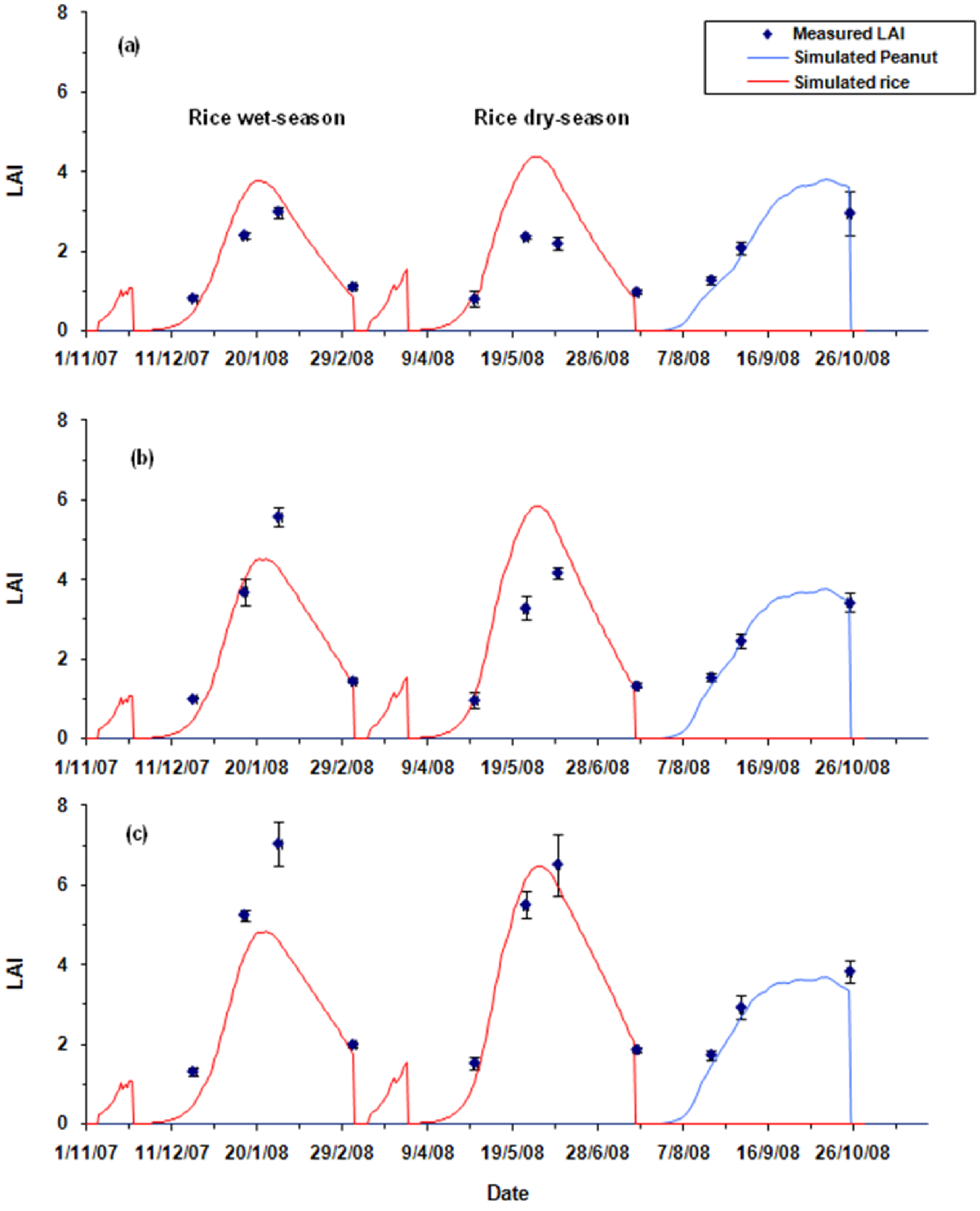

Figure 7.15 Simulated and measured leaf area index (LAI) of rice in CS irrigation treatment and peanut in whole year of rice-rice-peanut crops sequence in 2007-2008 at various N fertiliser rates; (a) is 0 kg ha^{-1} for both rice and peanut crops; (b) is 70 and 12 kg N ha^{-1} for rice and peanut crops respectively; (c) is 140 and 24 kg N ha^{-1} for rice and peanut respectively.

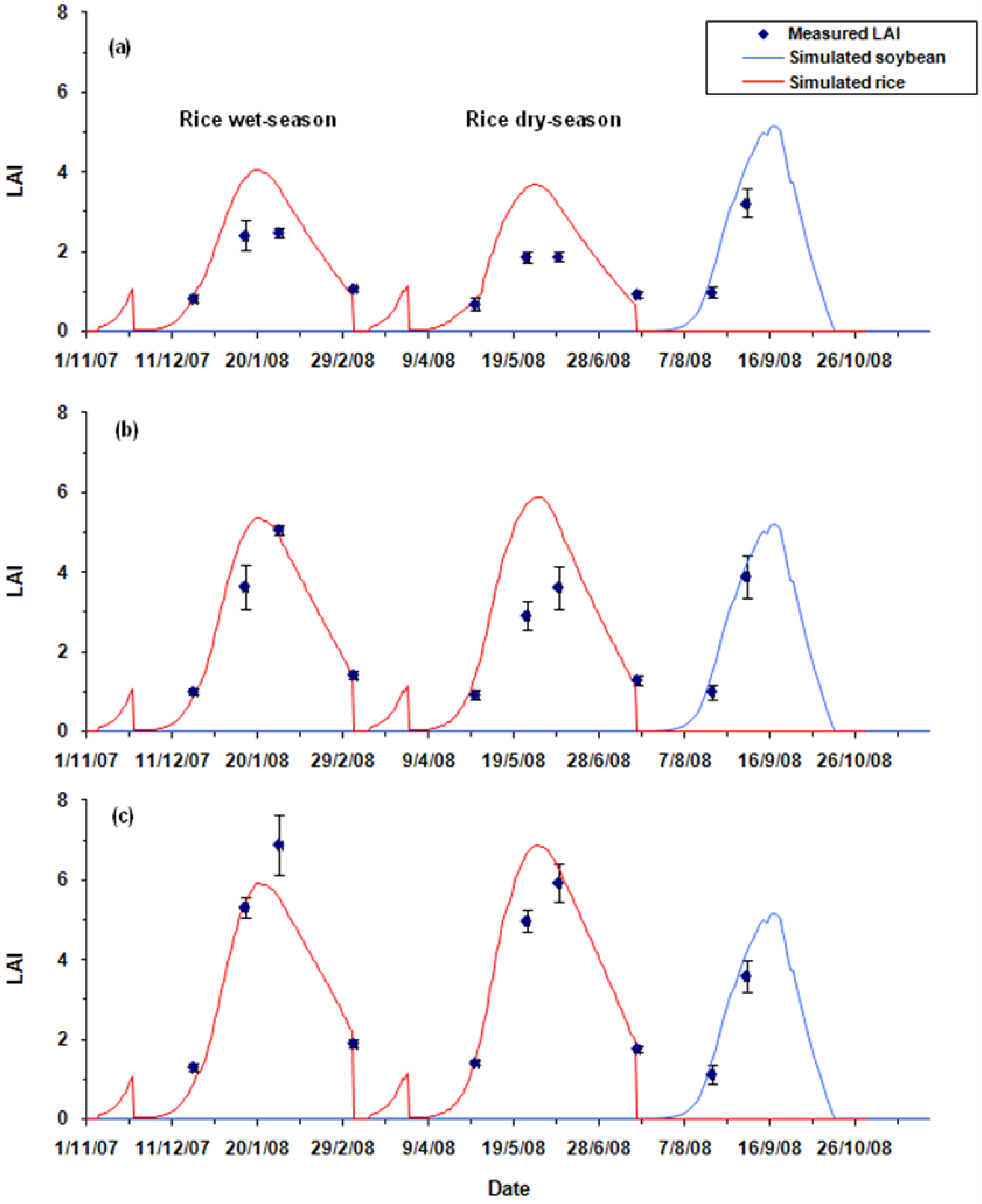

Figure 7.16 Simulated and measured leaf area index (LAI) of rice for ASNS irrigation treatment and soybean in whole year of rice-rice-soybean crops sequence at various N fertiliser rates; (a) is 0 kg ha^{-1} for both rice and soybean crops; (b) is 70 and 12 kg N ha $^{-1}$ for rice and soybean crops respectively; (c) is 140 and 24 kg N ha^{-1} for rice and soybean respectively.

Table 7. 11 Statistical analysis of model simulation of leaf area index (LAI) of rice at various irrigation treatments and legume crops (peanut and soybean) in rice-rice-legume crops sequence of 2007-2008 for calibration data sets.

Crops	Irrigation treatments	N	X_m (SD)	X_s (SD)	P(t)	α	β	R^2	$RMSE_a$	$RMSE_n$	EF
Rice	CS	24	2.77 (1.94)	2.82 (1.93)	0.93*	0.87	0.42	0.74	1	36.7	0.7
Rice	ASNS	24	2.57 (1.82)	3.13 (2.08)	0.32*	1.00	0.54	0.78	1	34.9	0.6
Legumes		18	2.42 (1.34)	2.34 (1.34)	0.90*	0.97	0.01	0.89	0.4	16.2	0.9

N, number of measured/simulated data pairs; X_m, mean of measured values in each season; X_s, mean of simulated values in each season; (SD), standard deviation of whole population; P(t), significance of paired t-test; in a column P(t), * means simulated and measured values are not significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, coefficient determination between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

7.3.1.8 N-uptake of rice and legume crops

Graphical comparison between simulated and measured N-uptake of rice for the CS and ASNS irrigation treatments and legume crops at various N fertiliser rates in rice-rice-legume crops sequence of 2007-2008 are shown in Fig. 7.17 and 7.18 respectively. In the wet season for both CS and ASNS irrigation treatments, simulated N-uptake closely matched with measured values during growth periods of rice at zero N fertiliser. However, overestimation of N-uptake increased as N fertiliser rates increased and more pronounced in the dry season than in the wet season for both CS and ASNS irrigation treatments. For legume crops, simulated N-uptake matched well with measured values during the growth period in all N fertiliser rates although measured values were slightly higher than simulated values in the peanut crop at harvesting stage as N fertiliser rates increased.

Table 7.12 shows the statistical analysis of model simulation for N-uptake of rice for various irrigation treatments, peanut and soybean in rice-rice-legume crops sequence of 2007-2008. Simulated mean and SD values were higher than measured values except for peanut, which indicated the model has over-predicted N-uptake as is shown in Fig. 7.17 and 7.18. The student’s t-test of N-uptake for rice in both CS and ASNS irrigation treatments and legume crops indicate that N-uptake was not significantly different between measured and simulated values at 95% confidence level. The values of α and R^2 for rice and legumes were close to one, which indicates the close agreement between measured and simulated values. In both CS and ASNS irrigation treatments, the values of β were higher than zero, indicating general overestimation of simulated values. Furthermore, the EF value for CS and ASNS and legume crops were close to one, indicating high performance of the model simulation. The RMSE of simulated LAI for rice and legume crops were lower than SD measured values. In general, these statistical indicators suggest that the performance of the model was acceptable in simulating the dynamics of N-uptake for rice in CS and ASNS irrigation treatments and legume crop in rice-rice-legume crops sequence in the tropical climate.

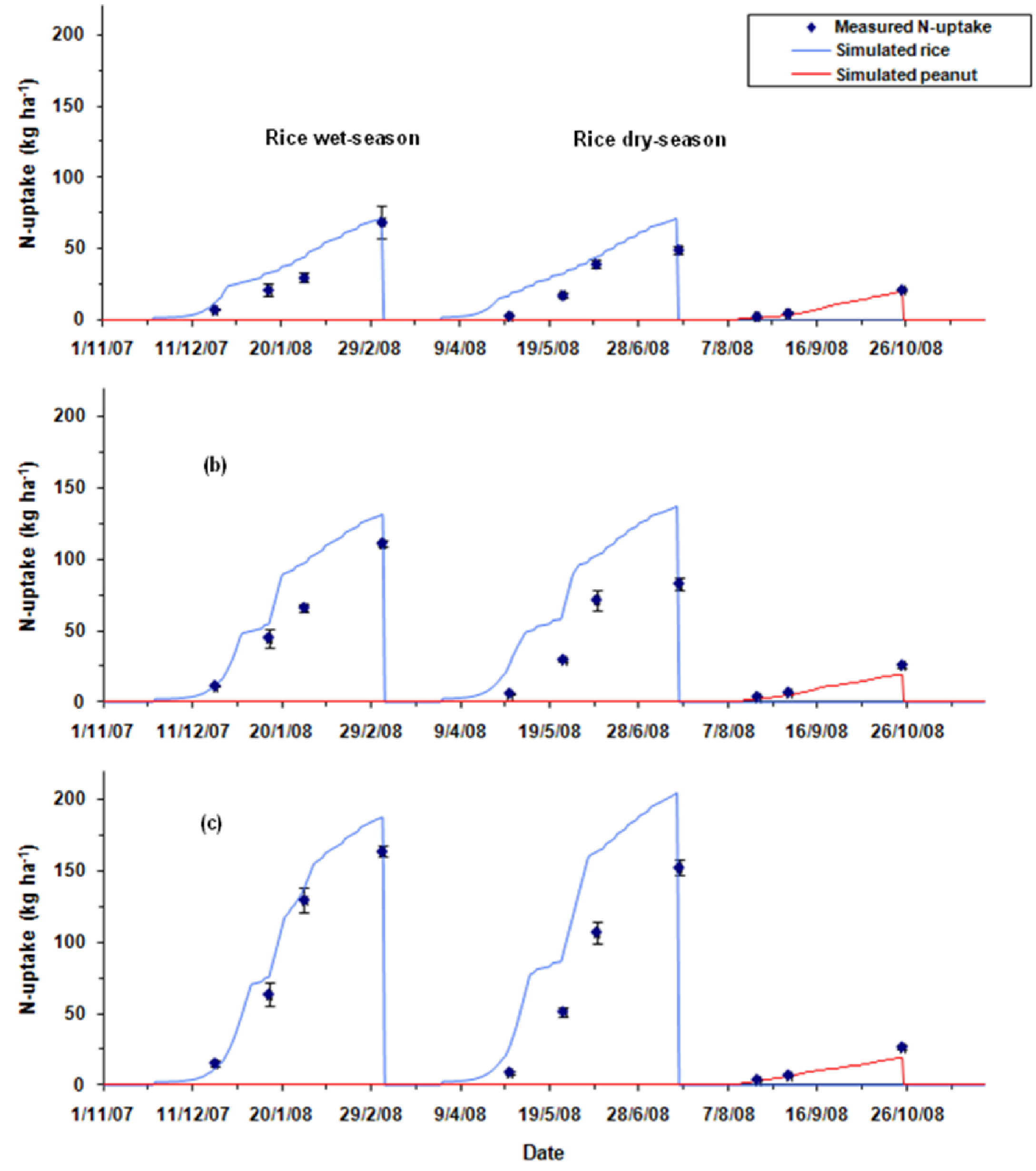

Figure 7.17 Simulated and measured N-uptake of rice in CS irrigation treatment and peanut in whole year of rice-rice-peanut crops sequence in 2007-2008 at various N fertiliser rates; (a) is 0 kg ha^{-1} for both rice and peanut crops; (b) is 70 and 12 kg N ha^{-1} for rice and peanut crops respectively; (c) is 140 and 24 kg N ha^{-1} for rice and peanut respectively.

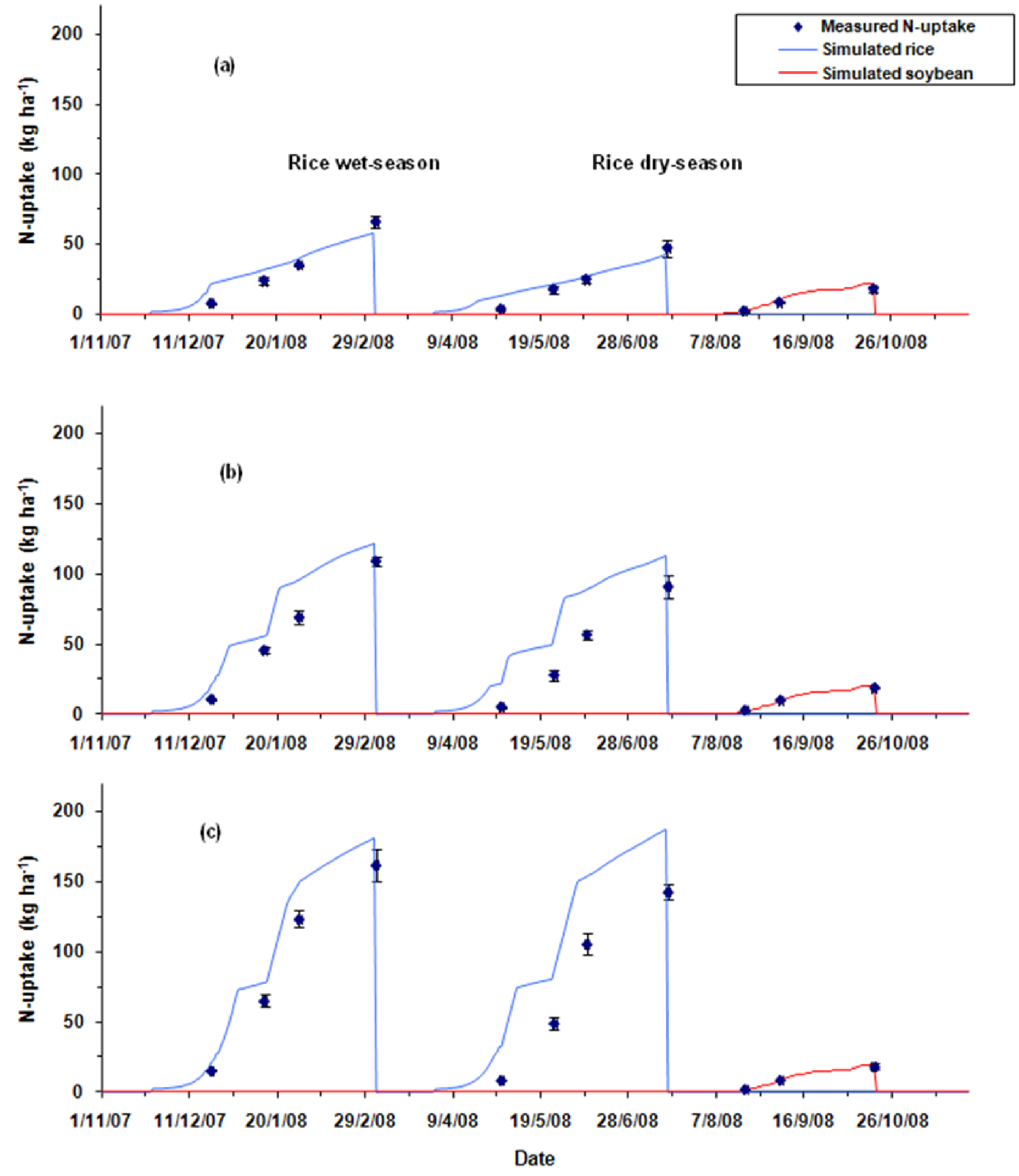

Figure 7.18 Simulated and measured N-uptake of rice in ASNS irrigation treatment and soybean in whole year of rice-rice-soybean crops sequence at various N fertiliser rates; (a) is 0 kg ha^{-1} for both rice and soybean crops; (b) is 70 and 12 kg N ha^{-1} for rice and soybean crops respectively; (c) is 140 and 24 kg N ha^{-1} for rice and soybean respectively.

Table 7.12 Statistical analysis of model simulation of N-uptake of rice, peanut and soybean in rice-rice-legume crops sequence of 2007-2008 for calibration data sets.

Variable	N	X_m (SD)	X_s (SD)	P(t)	α	β	R^2	$RMSE_a$	$RMSE_n$	EF
Rice-CS	24	56.3 (47.3)	77.3 (57.6)	0.17*	1.17	11.13	0.93	15.2	27	0.7
Rice-ASNS	24	56.0 (47.4)	71.9 (54.0)	0.29*	1.09	10.2	0.93	14.6	26.1	0.8
Peanut	9	11.3 (10.1)	8.7 (8.1)	0.60*	0.79	-0.23	0.98	1.1	10.1	0.9
Soybean	9	9.9 (6.96)	10.6 (8.21)	0.85*	1.17	-0.97	0.83	1.1	10.8	0.9

N, number of measured/simulated data pairs; X_m, mean of measured values in each season; X_s, mean of simulated values in each season; (SD), standard deviation of whole population; P(t), significance of paired t-test; in a column P(t), * means simulated and measured values are not significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, coefficient determination between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

7.3.2 Model validation

The APSIM-Oryza model was validated using field experiment data of rice-rice-legume crops sequence in 2008-2009. The details of field experiment are presented in Chapter 3 and brief description in section 7.3 in this chapter.

7.3.2.1 Floodwater dynamics during rice growth period

Figure 7.19 shows the dynamics of simulated and measured daily water depth during rice the growth periods in the CS and ASNS irrigation treatments in the wet-season of 2008/2009 and dry-season of 2009 for validation data sets. Simulated and measured daily water depth varied during the rice growth periods in both CS and ASNS irrigation treatments. The dynamics of simulated daily water depth generally followed the pattern of measured values during the rice growth period in both wet- and dry-seasons, although simulated maximum and minimum water depth varied with measured values. However, the performance of APSIM–Oryza to simulate daily water depth in CS was better in the calibration than that in the validation processes.

In the ASNS irrigation treatment, the performance of the model to simulate the dynamics of water depth during rice growth in validation data sets was similar to calibration data set. The dynamic of daily water depth between simulated and measured values varied most of the time during the rice growth period. Maximum and minimum water depth for simulated values mostly deviated from measured values. Moreover, when measured water depth was below the soil surface, the simulated values did not follow this pattern.

Table 7.13 shows statistical analysis of the performance APSIM-Oryza in simulating daily water depth during rice growth periods in the wet-season of 2008/2009 and dry-season of 2009. In the CS irrigation treatment for both wet and dry seasons, student’s t-test values were not significantly different at 95% confidence level and SD of measured values were higher than RMSE which indicate the performance of the model was acceptable. However, the values of slope (α) and coefficient of determinations (R^2) of linear regression between simulated and measured values were low and $RMSE_n$ and (β) were high. Moreover, the value of EF was negative in both wet- and dry-seasons. The performance of the model in the ASNS irrigation treatment to simulate water depth during rice growth was lower than that in the CS irrigation treatment. These indicators suggest that the performance of the model was poor in simulating the dynamics of daily water depth during rice growth periods in wet-/ and dry seasons of 2008/2009 and 2009 respectively for validation data sets.

When percolation rates of the soil in the second layer (hardpan soil layer) were reset at 17.1 mm day^{-1} for wet and dry seasons respectively for the CS irrigation treatment, performance of the model matched quite well (Fig. 7.20). The simulated values generally followed the measured values. The statistical analyses of goodness-of-fit parameters also indicated that simulated and measured values were matched quite good (Table 7.14). In this case, the performance of the model for validation data sets was similar to calibration data sets. This indicates that the disturbance of subsoil hardpan may affect the performance of the model to simulate the dynamics of daily ponded water depth during rice growth.

Simulated and measured water input during rice growth period in the CS and ASNS irrigation treatments in 2007/2008 and 2008 seasons for validation data sets is presented in Table 7.15. Simulated water input varied with irrigation treatments and seasons during rice growth period ranging from 1549 to 2210 mm in 2008/2009 season and from 1492 to 2190 mm in 2009 season. The performance of the model to reproduce irrigation input was close to measured values in both wet- and dry-seasons for CS and ASNS irrigation treatments. In the CS irrigation treatment, simulated total irrigation input was close to measured values with 0.5 % and 3.6 % difference to measured values in 2008/2009 and 2009 seasons respectively. The performance of the model to reproduce total irrigation input in ASNS irrigation treatment was similar to the CS irrigation treatment. Simulated total irrigation input in the ASNS irrigation treatment was 0.7% and 6.2% difference to measured values in 2008/2009 and 2009 seasons respectively. Moreover, the performance of the model to simulated total irrigation input in both the CS and ASNS irrigation treatments was greater in 2008/2009 season than that in 2009 season. This indicates that the simulated total irrigation input was in agreement with measured values, although simulated daily water depth was in less agreement with measured values.

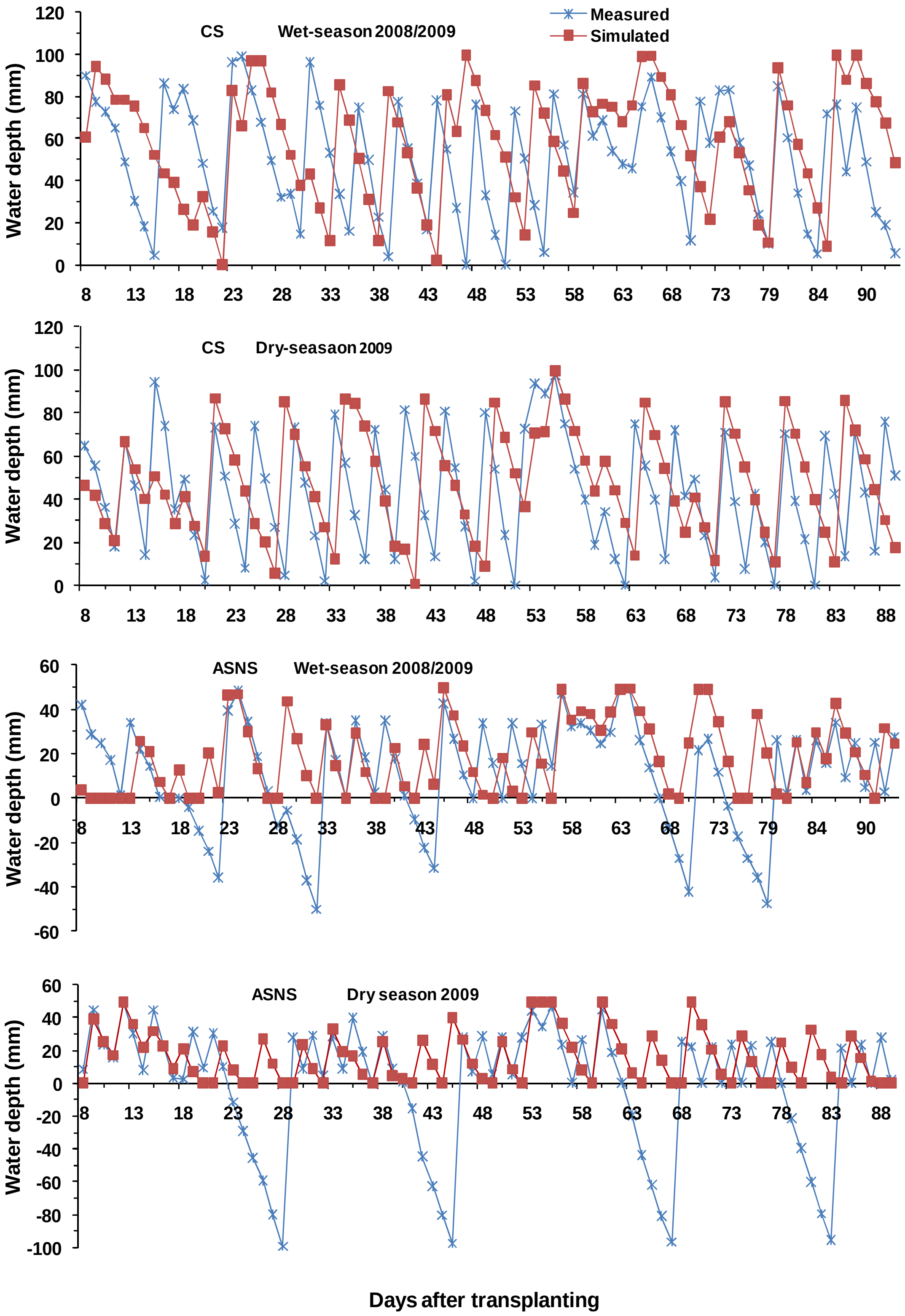

Figure 7.19 Simulated and measured daily depth during rice growth periods at 10.4 mm day^{-1} infiltration rate for continuously submerged (CS) and alternately submerged and non-submerged (ASNS) irrigation treatments in wet- 2008/2009 and dry-season 2009 for the validation data sets. Negative value of water depth indicates presence of water level below soil surface.

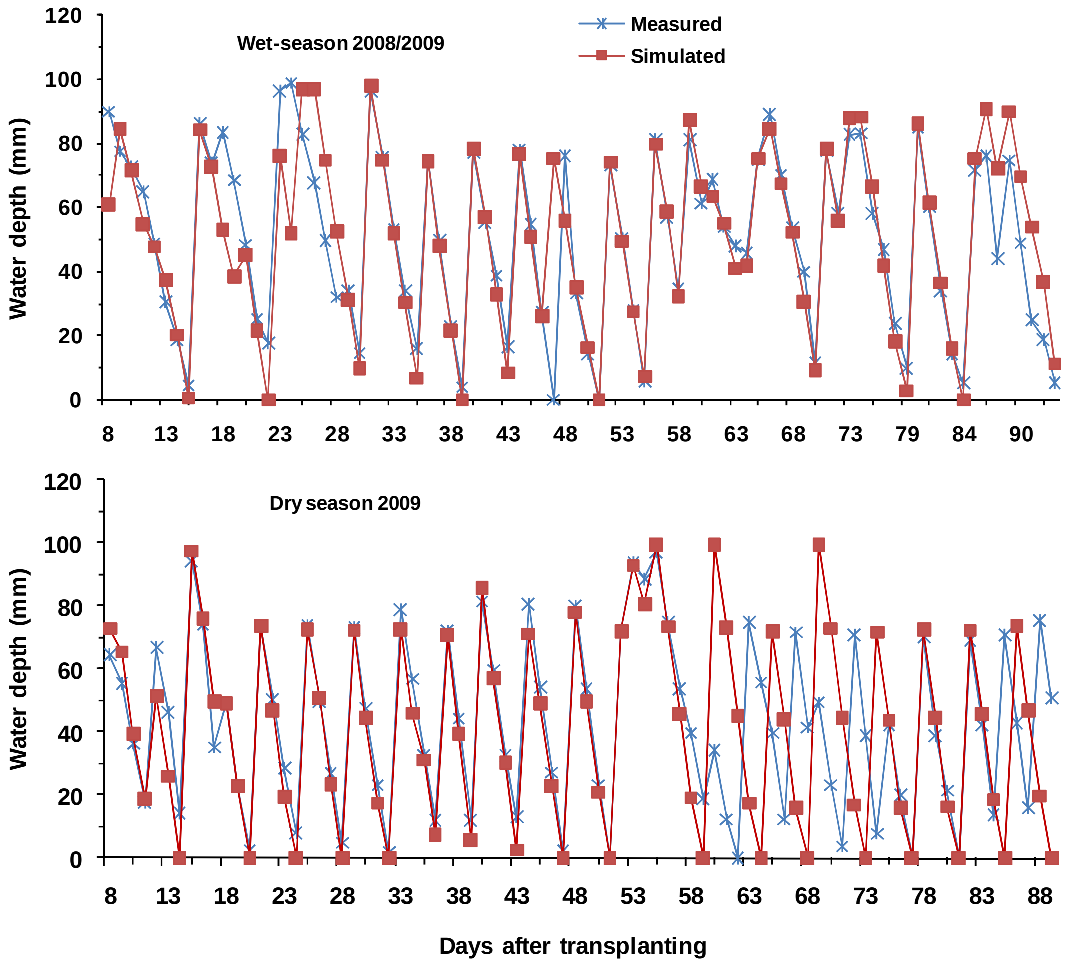

Figure 7.20 Simulated and measured daily water depth during rice growth period when percolation rates reset to 17.1 mm day^{-1} in continuously submerged (CS) irrigation treatment in wet-season of 2008/2009 and dry-season of 2009 for the validation data sets.

Table 7.13 Statistical analysis of model simulation for daily water depth at CS and ASNS irrigation treatments in wet- and dry-seasons of 2008/2009 and 2009 for validation data sets at percolation rate of 10.4 mm d^{-1}.

Indicators	CS		ASNS	
	2008/2009	2009	2008/2009	2009
N	90	90	90	90
X_m (SD)	50.18 (27.6)	42.76 (27.33)	10.28 (24.1)	1.28 (38.7)
X_s (SD)	56.15 (27.1)	43.80 (24.74)	18.35 (16.8)	15.8 (15.5)
P(t)	0.08*	0.22*	0.01	0.01
a	0.2	0.2	0.28	0.1
b	48.6	40	15.46	15.9
R^2	0.04	0.04	0.16	0.1
$RMSE_a$	27.1	24.4	15.4	15.1
$RMSE_n$	54	57.2	50.29	82.7
EF	-0.69	-0.49	-0.04	-0.16

N, number of measured/simulated data pairs; X_m, mean of measured values; X_s, mean of simulated values; (SD), standard deviation of whole population; P(t), significance of paired t-test; in a column P(t), * means simulated and measured values are not significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, determination coefficient between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

Table 7.14 Statistical analysis of model simulation for daily water depth at CS irrigation treatment when percolation rates was reset to 17.1 mm d^{-1} for wet-season of 2008/2009 and dry-season of 2009 for validation data sets.

Indicators	Rice seasons	
	2008/2009	2009
N	90	90
X_m (SD)	50.18 (27.6)	42.76 (27.33)
X_s (SD)	50.42 (28.1)	40.93 (30.74)
P(t)	0.94	0.69
a	0.88	0.69
b	6.49	11.5
R^2	0.74	0.37
$RMSE_a$	14.3	24.5
$RMSE_n$	28.5	57.2
EF	0.72	0.11

N, number of measured/simulated data pairs; X_m, mean of measured values; X_s, mean of simulated values; (SD), standard deviation of whole population; P(t), significance of paired t-test; in a column P(t), * means simulated and measured values are not significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, determination coefficient between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

Table 7.15 Measured and simulated irrigation input during rice growth periods in 2008/2009 and 2009 seasons for validation data set.

Seasons	Irrigation input (mm)	CS				ASNS			
		Measured (M)	Simulated (S)	Difference (M-S)	Difference (%)	Measured (M)	Simulated (S)	Difference (M-S)	Difference (%)
2008/2009	Irrigation	1234.0	1245.3	-11.3	-0.9	689	700	-10.6	-1.5
	Rainfall	964.7	964.7	0.0	0.0	849	849	0.0	0.0
	Total irrigation input	2198.7	2210.0	-11.3	-0.5	1538.0	1548.6	-10.6	-0.7
2009	Irrigation	1864	1781	82.7	4.4	1198	1100	98.2	8.2
	Rainfall	409	409	0.0	0.0	392	392	0.0	0.0
	Total irrigation input	2272.4	2189.8	82.7	3.6	1590.5	1492.3	98.2	6.2

7.3.2.2 Organic carbon dynamics of soil

Table 7.16 shows the goodness-of-fit parameters of OC at different soil layers during crop growth periods of rice-rice-legume crops sequence in 2008-2009. The performance of the model in simulating the dynamics of soil OC at various soil depths during crop growth periods were similar to the calibration data sets. The measured values of OC was more scattered than simulated values as indicated by lower R^2 values, indicating dynamics change organic carbon in the field although measured OC values decreased as soil depth increased and simulated values followed the trend. The student’s t-test values were greater than 0.05 in layer 2 and 4, indicating that the simulated values are not statistically different with measured values, while t-test values fir layer 1 and 3 were ≤ 0.05. Except for layer 1, each soil layer has a single simulated value of OC as shown by SD = 0 which indicated the resistance of OC to decomposition in the model. The α values were small in all soil layers, which indicated the general underestimation of simulated values although the β values were close to zero. Moreover, the correlations between observed and simulated values were weak in all soil layers as indicated by very low coefficient of determinations (R^2). The EF values in soil layers 2 and 4 were positive although it was small while in layers 1 and 3 were negative. This suggests that the performance of the model in simulating the dynamics of soil OC during crop growth periods of rice-rice-legume crops sequence in 2007-2008 was poor in all soil layers.

Table 7.16 Statistical analysis of model simulation for organic carbon (OC) in rice-rice-legume crops sequence of 2008-2009 at various soil layers for validation data sets.

parameters	N	X_m (SD)	X_s (SD)	P(t)	α	β	R^2	$RMSE_a$	$RMSE_n$	EF
Layer 1	48	1.3 (0.13)	1.38 (0.09)	0.02	0.04	1.33	0.38	0.007	0.4	-0.25
Layer 2	48	0.21 (0.08)	0.38 (0.0)	0.39*	0.05	0.39	0.04	0.002	0.55	0.027
Layer 3	48	0.21 (0.03)	0.23 (0.0)	0.05	0.004	0.23	0.06	0.005	0.22	-0.028
Layer 4	48	0.18 (0.05)	0.19 (0.0)	0.1*	0.006	0.19	0.08	0.003	0.17	0.09

N, number of measured/simulated data pairs; X_m, mean of measured values; X_s, mean of simulated values; (SD), standard deviation of whole population; P(t), significance of unpaired t-test; in a column P(t), * means simulated and measured values are not significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, determination coefficient between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

7.3.2.3 Nitrate-N and ammonium-N dynamics of soil

The performance of the model in simulating nitrate-N (NO_3-N) and ammonium-N (NH_4-N) dynamics in soil during rice and legume crops growth periods at various irrigation and N fertiliser treatments for validation data sets are presented in Table 7.17. In general, the performance of the model in simulating NO_3-N and NH_4-N dynamics in soil was similar to the calibration data sets. The model was generally poor in simulating the dynamics of NO_3-N and NH_4-N concentrations in soil during the rice and legume crops growth periods. The values of t-test for NO_3-N and NH_4-N in both irrigation and N fertiliser treatments were highly significant. Furthermore, EF values in all treatments were negative and R^2 values were low. These indicators suggest that the model had discrepancy to simulate the dynamics of NO_3-N and NH_4-N concentration in soil in rice-rice-legume crops rotation.

7.3.2.4 Biomass, yield and leaf area index of rice and legume crops

Table 7.18 shows goodness-of-fit parameters of the model to simulate biomass, yield and leaf area index of rice and legume crops in rice-rice-legume crop rotation in 2008-2009 for validation data set. In CS and ASNS irrigation treatments for rice biomass, P(t) values (0.79 and 0.81 for CS and ASNS respectively) indicated that simulated was not significantly different from measured biomass. Furthermore, the values of α, R^2 and EF were close to one and $RMSE_a$ values were lower than SD of measured values, although β values in CS (-160 kg ha^{-1}) and ASNS (235 kg ha^{-1}) treatments were negative and positive respectively, indicating underestimation and overestimation of simulated values respectively. The performance of the model to simulate rice biomass in validation was similar to calibration. These goodness-of-fit parameters suggest that the model adequately reproduced similar biomass to measured values in both calibration and validation data sets. Similar to rice biomass, the model also reproduced peanut and soybean biomass quite good with p(t) values did not significantly different between simulated and measured legume biomass. However, t-test value for soybean was higher in calibration than in validation processes, which indicated better performance of the model in calibration data sets.

Table 7.17 Statistical analysis of model simulation for nitrate-N and ammonium-N concentration in soil at various irrigation treatments and N fertiliser rates in rice-rice-legume crops sequence of 2008-2009 for validation data sets.

Variable	Treatment	N	X_m (SD)	X_s (SD)	P(t)	α	β	R^2	$RMSE_a$	$RMSE_n$	EF
NH_4-N	CS	132	4.21 (4.39)	1.35 (2.4)	<0.001	0.83	-2.14	0.46	3.2	75.9	-0.48
	ASNS	132	4.06 (4.37)	0.71 (2.42)	<0.001	0.46	-1.17	0.43	1.8	44.4	-0.58
	F0	88	2.57 (1.66)	0.19 (0.18)	<0.001	0.005	0.004	0.18	0.23	8.88	-3.73
	F1	88	3.86 (3.21)	0.74 (1.43)	<0.001	0.47	-0.06	0.29	1.78	46.2	-1.45
	F2	88	5.98 (6.11)	2.17 (3.88)	<0.001	0.77	-2.45	0.44	4.16	69.6	-0.47
NO_3-N	CS	132	5.32 (4.8)	0.35 (0.9)	<0.001	0.07	-0.02	0.14	0.85	15.89	-0.96
	ASNS	132	5.40 (4.8)	0.82 (1.3)	<0.001	0.16	-0.002	0.3	1.12	20.76	-0.69
	F0	88	3.69 (3.3)	0.43 (0.7)	<0.001	0.09	0.1	0.19	0.62	16.88	-0.86
	F1	88	5.32 (4.6)	0.50 (0.9)	<0.001	0.09	0.04	0.22	0.77	14.38	-0.99
	F2	88	7.07 (5.7)	0.82 (1.7)	<0.001	0.13	-0.12	0.21	1.5	21.26	-1.04

N, number of measured/simulated data pairs; X_m, mean of measured values in each season; X_s, mean of simulated values in each season; (SD), standard deviation of whole population; P(t), significance of paired t-test; in a column P(t), * means simulated and measured values are not significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, determination coefficient between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

Table 7.18 Statistical analysis of model simulation for biomass, yield and leaf area index (LAI) at various irrigation treatments of rice-rice-legume crops sequence in 2008-2009 for validation data sets.

Parameter	Variable	N	X_m (SD)	X_s (SD)	P(t)	α	β	R^2	$RMSE_a$	$RMSE_n$	EF
Rice-CS	Biomass	24	5251 (4087)	4926 (4208)	0.79*	0.97	-160	0.86	1534	19.2	0.86
Rice-ASNS	Biomass	24	5100 (3973)	5394 (4363)	0.81*	1.01	235	0.85	1736	34.0	0.81
peanut	Biomass	24	3988 (2647)	3840 (42341)	0.84*	0.86	407	0.95	548	13.7	0.93
Soybean	Biomass	24	3133 (2193)	3971 (2464)	0.26*	1.14	410	0.94	612	19.6	0.74
Rice	yield	12	5101 (1337)	5122 (1674)	0.97*	1.18	-917	0.90	570	11	0.80
Rice-CS	LAI	24	2.62 (1.80)	2.82 (1.64)	0.69*	0.74	0.88	0.66	1	37.2	0.60
Rice-ASNS	LAI	24	2.47 (1.68)	3.36 (1.89)	0.10*	0.94	1.04	0.69	1.1	43.3	0.30
legume	LAI	18	2.23 (1.07)	2.69 (1.1)	0.44*	0.63	1.28	0.93	0.5	20.2	0.70

N, number of measured/simulated data pairs; X_m, mean of measured values in each season; X_s, mean of simulated values in each season; (SD), standard deviation of whole population; P(t), significance of paired t-test; in a column P(t), * means simulated and measured values are not significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, determination coefficient between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

The performance of the model to simulate rice yield was also similar to biomass. The values of p(t), α, R^2 and EF were close to one and RMSE value was lower than SD measured values. The simulated rice yields were about 897 kg ha^{-1} and 917 kg ha^{-1} lower than measured yields in calibration and validation processes, respectively. For peanut and soybean, the simulated yields were a close fit with measured values (Table 7.19). In peanut, simulated yields were slightly underestimated by 2.78% at zero N fertiliser as indicated by a positive value of the difference between measured and simulated values. However, overestimation of simulated values increased as N fertiliser rates increased (as indicated by a negative values of the different between measured and simulated values) although these increases were small with less than 10%. In soybean, the model overestimated yield in all N fertiliser rates ranging from 23% to 29%.

The model simulated leaf area index (LAI) of rice and legume crops quite well in the validation data sets. The values of p(t) indicated that measured values was not significantly different with simulated LAI for both rice and legume crops. Moreover, the values of a R^2 and EF were high and RMSE values were lower than SD measured values. However, the performances of the model in the calibration data sets were better than in the validation data sets, as indicated by the values of p(t), α, R^2 and EF being higher in the calibration than in the validation.

7.3.2.5 N-uptake of rice and legume crops

Table 7.20 shows goodness-of-fit parameters of N-uptake at various irrigation treatments of rice and legume crops in the rice-rice-legume crop sequence in the 2008-2009 for validation data sets. Simulated N-uptake of rice and legume crops matched well with measured values. The values of student’s t-test indicated the simulated N-uptake of rice and legume crops were not significantly different with measured values. Furthermore, the values of α, R^2 and EF were close to one and RMSE values were lower than SD measured values. The performance of the model to simulate N-uptake in the validation was similar to the calibration data sets, although p(t) values for rice at ASNS treatment was smaller in the validation data set. All goodness-of-fit parameters of N-uptake indicate a close agreement between simulated and measured values.

Table 7.19 Measured and simulated yield of peanut and soybean at various N fertiliser rates in dry-season of 2009 for validation. The values in bracket indicate standard deviation (n = 3).

Crops	N rates (Kg ha^{-1})	Measured (M)	Simulated (S)	M-S	Difference (%)
Peanut	0	2120 (225)	2062	59	2.78
	12	2109 (181)	2132	-23	-1.07
	24	1969 (286)	2145	-175	-8.90
Soybean	0	2039 (54)	1520	519	25.46
	12	2150 (50)	1519	631	29.35
	24	1961 (171)	1507	454	23.14

Table 7.20 Statistical analysis of model simulation for N-uptake of rice at various irrigation treatments and legume crops in rice-rice-legume crops sequence of 2008-2009 for validation data sets.

Indicators	Rice		Peanut	Soybean
	CS	ASNS		
N	24	24	9	9
X_m (SD)	66.9(44.9)	63.9 (52.5)	9.1 (5.7)	10.3 (7.4)
X_s (SD)	75.8 (56.5)	84.4 (56.5)	10.5 (8.1)	13.4 (7.6)
P(t)	0.25*	0.06*	0.56*	0.39*
a	1.16	1.27	1.38	0.91
b	6.98	12.8	-2.04	4.01
R^2	0.96	0.91	0.99	0.83
$RMSE_a$	11.2	17.7	0.7	3.6
$RMSE_n$	18.9	31.4	8.1	35.1
EF	0.8	0.3	0.8	0.6

N, number of measured/simulated data pairs; X_m, mean of measured values in each season; X_s, mean of simulated values in each season; (SD), standard deviation of whole population; P(t), significance of paired t-test; in a column p(t), * means simulated and measured values are not significantly different at 95% confidence level; α, slope of linear correlation coefficient between measured and simulated values; β, intercept of linear relation between measured and simulated values; R^2, determination coefficient between measured and simulated values; $RMSE_a$, absolute root mean square error; $RMSE_n$, normalised root mean square error; EF, efficiency of forecasting.

7.4 Discussion

The APSIM-Oryza allows continuous simulation of soil conditions, following initialization at the start of a simulation session, including rice–rice-legume crop sequences, user-specified in terms of crop management such as sowing and transplanting dates, crop density, and N management, i.e. dates, rates, types and application methods of nitrogenous fertilisers. Furthermore, the APSIM-Oryza allows simulation of organic carbon and nitrogen (NO_3 and NH_4) dynamics in the anaerobic soil conditions during the submerged rice season and in the aerobic soil conditions during the dry season of legume crops (Gaydon et al., 2009).

In the CS irrigation treatment, the APSIM-Oryza performs well in simulating the dynamics of floodwater during the rice growth period in the calibration set, as assessed through graphical comparison and goodness-of-fit parameters. However, as crop sequences progress with time, the performance of the model was poor to simulate floodwater dynamics in the CS irrigation treatment in the validation set. This is probably due to increase in soil percolation rate as the result of the disturbance of the subsoil hardpan at sampling time of the soil in each plot. Although the holes were filled with clay mud after soil sampling, frequent soil sampling on small plots would destroy hardpan systems leading to increased percolation rates. Furthermore, water input from irrigation increased in each season being higher in the dry season than in the wet season (see Chapter 4, section 4.2). In this case, percolation rate of the second layer of soil (20-40 cm depth) in the model was changed to match the measured values. When percolation rate in the model was reset to the higher values of 17.1 mm day^{-1} for the validation data set in the wet-season of 2008/2009 and dry-season of 2009, the model performance was quite satisfactorily (Fig. 7.19).

In contrast, the APSIM-Oryza was poor in simulating the dynamics of floodwater during the rice growth periods in the ASNS irrigation treatment. During the nonsubmergence period, water depth was below the soil surface at about 10 cm before re-irrigation was applied. The APSIM-Oryza was less satisfactory to reproduce the dynamic of daily floodwater in this case. This is because the APSIM was not intended to simulate the dynamic of daily ponding depth under water limitation whereas a new APSIM-Pond module recently developed and communication with other modules (SoilN and SoilWat) in the systems have changed. The main task of this study was to evaluate the performance of the APSIM in simulating crops, water and soil variables under a normal condition. This remains a future challenge of the model to precisely simulate water dynamics of irrigated rice under water limitation. However, simulated total water input in the ASNS irrigation treatment during rice growth period was close to the measured values (Table 7.5 and 7.11). This indicates a good performance of the model to simulate total water input in the lowland rice-based cropping systems under water limitation, although simulated the daily water depth was in less agreement with measured values. The model generally could be used to simulate lowland rice-based cropping systems under limited and non-limited water irrigation scenarios in terms of total water input. The capability of the APSIM to simulate rice-based farming systems under water limitation is very important as water is becoming scarce and adapting farming systems to reduced availability of irrigation water is an emerging research issue in irrigated districts throughout the globe.

The dynamics of floodwater resulting from the model was comparable with the ORYZA2000 model reported by Belder et al. (2007) and Feng et al. (2007). They found that the R^2 was lower, the value of α was greater than 1 and β deviated from 0 for simulated and measured field water depth. Although the ORYZA2000 model was less accurate in simulating water depth dynamics during the rice growth periods, Belder et al. (2007) used the simulated results to calculate water balance under experimental conditions, and to extrapolate to the different seasons and soil types. They argued that the time step of integration in the ORYZA2000 is one day, and it is unknown whether rainfall events occurred during the night (i.e., after integration of state variables in the model occurred) or during the day (i.e., before integration took place). The integration of the state variables always takes place at the end of the day, and the model always assumes rainfall to have taken place during the day. Similarly, irrigations were sometimes applied before the measurement of ponded water depth or soil water tension, and sometime after. If irrigation is applied in the morning, a considerable amount of the water would already have been lost through evapotranspiration and percolation by the end of the day, and less water would have been lost if irrigation applied in the afternoon. In APSIM, the time step of integration is also one day and these explanations are applied in the model (Keating et al. 2003).

Soil inorganic N (NO_3-N and NH_4-N) varied considerably following the crop growth seasons and reached peaks when N fertiliser is applied. The APSIM-Oryza was generally poor in simulating the dynamics of NO_3-N and NH_4-N concentration in soil during rice and legume crops growth periods under CS and ASNS irrigation management and N fertiliser rates. Nitrogen fertiliser was applied at 8, 30 and 54 days after transplanting (DAT) and soil was sampled before N fertiliser applied. Simulated NH_4-N reached a peak at 20-24, 31-33 and 57-59 DAT. This indicates that the rate of urea hydrolysis at the first N fertiliser application was very low while at second and third applications were too fast. Simulated NH_4-N and NO_3-N of soil declined rapidly after top dressing compared with higher measured values. Measured NH_4-N and NO_3-N concentrations of soil at 140 kg N ha^{-1} during rice growth periods were around 18 and 5 kg ha^{-1} respectively and around 8 and 20 kg ha^{-1} respectively during legume crops growth periods. However, simulated NH_4-N and NO_3-N were close to zero for most of the time. Low values of simulated soil NO_3-N concentration suggested that the model is probably underestimating nitrification rate and/or overestimating denitrification.

Measured NO_3-N concentration in soil increased at deeper soil layers, indicating that NO_3-N leaching occurred downward which probably relates to the coarse-texture of soil used in this study, whereas simulated values were almost zero at deeper soil layers. In an ideal irrigated rice fields with fine-textured soil, leaching losses of N are low because of restricted percolation (Buresh et al., 1989; George et al., 1992). However, in coarse-textured soils with high permeability, the loss of N through leaching can be substantial because of high percolation and drainage of water in these soils in which NO_3-N is leached downward (Shrestha and Ladha 2002). High NO_3-N concentration in soil is expected in the dry season during the legume crops growth in a rice-rice-legume crops sequence because the drying of the soil at the end of the rice crop is suitable for nitrification. However, accumulated NO_3-N during the dry season is prone to loss by leaching during rice flooding in the wet season (Buresh et al. 1989; George et al. 1992; De data, 1995).

The different response of net mineralisation to N fertiliser between rice and legume crops probably is the result of differences in soil inorganic N content in the zero fertiliser treatment. During irrigated rice growth period, soil inorganic N content is low at zero N fertiliser application due to low mineralisation under flooded conditions (Fig. 7.4 – 7.11) (Shibu et al., 2006; Jing et al., 2010). During the dry season of the legume crops growth periods, soil inorganic N content increased to a relatively high level before N fertiliser application to the legume, which then rapidly declined, resulting in a slightly positive response of net N mineralisation. APSIM has reproduced this pattern although the simulated values were lower than measured values.

In fine textured soils of most rice-growing environments, soil oxygen is rapidly depleted when the soils are flooded and soil NO_3-N is prone to loss by denitrification as well as leaching. Soil NO_3-N is normally negligible at the end of irrigated rice season (De data, 1995; Buresh et al, 1989). This is a basic assumption of APSIM that, when there is a pond on the surface, the soil oxygen levels are very quickly reduced (oxygen depleted) and all soil NO_3 are denitrified and lost. However, this assumption may not be generally correct for a coarse-textured soil with high percolation rates where there was NH_4-N and NO_3-N concentration in soil under anaerobic conditions (as was case in this study) although their values were small (Fig. 7.10 and 7.11). Other studies also found similar results (Pathak et al., 2004; Pande and Becker, 2003; Aulakh et al., 2000). Pathak et al. (2004) reported that measured NO_3-N concentration of a loam soil in Delhi India was always around 10 kg ha^{-1} during the rice growth period receiving 120 kg N ha^{-1}.

The relative complexity of modelling N dynamics in the alternation of anaerobic and aerobic conditions in the rice-rice-legume crops sequence is well known and the weaknesses of the simulation have been reported for other models as well, such as CERES-Rice (Pathak et al., 2004; Timsina and Humphreys, 2006). Pathak et al. (2004) evaluated the CERES-Rice model (ver. 4.0), where this source code of APSIM-Pond was mainly derived (Gaydon et al., 2009), for soil mineral N and loss processes from rice-wheat cropping systems in Delhi and Punjab. They found that simulation of soil mineral N in the surface layer (0-15 cm) was generally poor. Based on this study and others, the behaviour of the nitrification and denitrification in the model under anaerobic and aerobic conditions of coarse-texture soil need further evaluation.

The model performed quite good in simulating the dynamic of soil organic carbon during the rice and legume crops growth period. Measured OC decreased in deeper soil layers and simulated values followed this pattern, although the measured OC was more scattered than simulated values. This indicated that mineralisation of OC in the model was slower than in the field. When soil is flooded, oxygen is almost depleted due to much slower oxygen diffusion in water, creating an anaerobic condition (Brune et al., 2000) and decomposition of organic substrates takes place in the absence of oxygen. Decomposition of organic substrates under anaerobic conditions is slower than under aerobic conditions (Dobernmann and Witt, 2000; Sahrawat, 2004; Bird et al., 2003) with the rates of organic substrates decomposition in the first-order reaction are about 2 to 3 times lower than that under aerobic condition (DeBusk and Reddy, 1998; Jing et al., 2010). This condition is applied to APSIM-SoilN module (Gaydon et al., 2009).

The APSIM-Oryza generally predicted rice and legume crops variables satisfactorily for the rice-rice-legume crops sequence in both calibration and validation data sets. Gaydon et al. (2009) and Zhang et al. (2007) also observed similar results of the capability of the model to simulate rice crop variables. Simulated biomass followed the pattern of measured values during rice and legume crops growth periods with better performance of the model in the CS than that in the ASNS irrigation treatments. The model performed well in simulating rice biomass and N-uptake, although simulated values were slightly higher in the dry-season as N fertiliser rates increased. This was probably due to inadequate simulation of nitrogen immobilisation during residue decomposition following the first rice crop (Suriadi et al., 2009). This is also related to higher simulated LAI and N-uptake as N fertiliser rates increased.

The robustness of the APSIM performance under water (such as CS and ASNS) and N management in rice-based farming systems is of particular importance. Rice is one of the biggest users of the world’s developed freshwater resources (Tuong and Bouman, 2003; Bouman and Tuong, 2001; Tuong et al., 2005). Improving the water use efficiency will be one of the major challenges in irrigated rice-based production (Keerthisinghe, 2006). In this study, APSIM-Oryza was only evaluated with respect to crop variables (biomass, yield, LAI and N-uptake), soil variable (organic carbon, nitrate-N and ammonium-N) and water (ponded depth) in rice-rice-legume crops sequence in tropical climate. The transportation and transformation of N in the systems such as nitrification, denitrifation and fixation under anaerobic and aerobic conditions need further evaluation, which is hampered by the availability of suitable data set to test the model. Such detailed experimental data sets are required including information on above-ground and below-ground processes to enable a more comprehensive evaluation of APSIM-Oryza in rice-based farming systems.

If the APSIM-Oryza is well tested and validated, it could be used with confidence to explore management options to increase resource use efficiency, such as water-saving irrigation (Belder et al., 2007; Feng et al., 2007) and efficient N management (Jing et al., 2007). Suriadi et al. (2009) reported that the ASNS irrigation treatment on coarse soil could result in water saving of 36-44% compared with the CS irrigation treatment without significantly reducing yield and components of yield, and biomass. Belder et al. (2004) found similar results in a high clay content of soil (silty clay) with percolation rates of 1-4.5 mm per day in a shallow ground water table. APSIM-Oryza could be applied to explore the consequences of different water management on productivity, and used to contribute a better understanding of underlying biophysical processes as well as to identify potential trade-offs between productivity and environmental goals. Although substantial improvements have been made to the APSIM-SoilN module, further work is required before it could be used to simulate N-dynamics satisfactorily.

7.5 Concluding remarks

APSIM-Oryza allows continuous simulation of crops, water and soil variables in rice-based farming systems with sufficient accuracy to capture the major effects of N and irrigation management on lowland rice and legume crops in rice-rice-legume crops sequence in the tropical climate. The study showed that generally simulated crop variables (biomass, yield, LAI and N-uptake) under both CS and ASNS irrigation treatments and various N fertiliser application rates matched with measured values. The dynamics of daily floodwater were simulated quite good by the model in the CS treatment and total water input matched with measured values. However, inorganic N dynamics and daily floodwater dynamics in the ASNS irrigation treatment needs further improvement for better prediction of growth and development and N- and water-related processes, particularly in coarse-textured soils with a high percolation rate.

APSIM-Oryza has considerable potential for the ex-ante evaluation of soil, water and crops management practices in rice-based farming systems. Adequate and good quality experimental data sets would be required for further improvement of key model processes.

CHAPTER VIII

General discussion and conclusions

To meet the food demands of growing populations, rice production needs to be increased or maintained in the next few decades. However, there is an increasing threat to the productive capacity of rice environment with water scarcity, drought, salinity, flooding and climate change. Because of these stresses rice production needs to be water efficient by being able to grow more rice with less water.

Various water-saving technologies such as alternate submerged and non-submerged, saturated soil culture, raised-bed culture and aerobic rice can all reduce water input with variable reduction in yield depending on the environment where the technologies are being used such as soil properties including texture, ground water depth and climate. Most water-saving technologies for irrigated rice have been developed for fine-textured soils which have low percolation and seepage rates with little attention to coarse-textured soils. Irrigated rice fields on fine-textured soils also have low leaching losses of N (in NO_3-N form) that highly contrast with coarse-textured soils due to the difference in permeability.

These factors have led to examining the hypothesis in this work (Chapter I) that the water use productivity of rice can be improved without significant decrease in yield through improved water management. The overall aim is to improve crop growth simulation capability that captures the essence of temporal variation in depth of ponding and the concentration of available forms of N in rice and other crops within the sequence to allow testing of various water and nitrogen management strategies.

A series of field experiments were conducted using the rice-rice-peanut and rice-rice-soybean crop sequences for a period of 2 years (2007--2009) to meet the objectives described above and as detailed in Chapter I. All methods and results of these field experiments were described in full detail in the previous chapters. This chapter provides a summary of the main findings of this study to indicate overall outcomes (conclusions) and the direction for future research in this area.

8.1 Productivity of rice and legumes

The results of this experiment showed that biomass, yield and various components of yields were not significantly different between ASNS and CS treatments over four rice seasons. There was also a saving of 36-44% of irrigation water with ASNS over CS (Chapter IV). This led to an overall increase of 52% in water productivity for ASNS over CS. As shown in Fig. 8.1, yield of rice remained relatively constant over a considerable range of total water used.

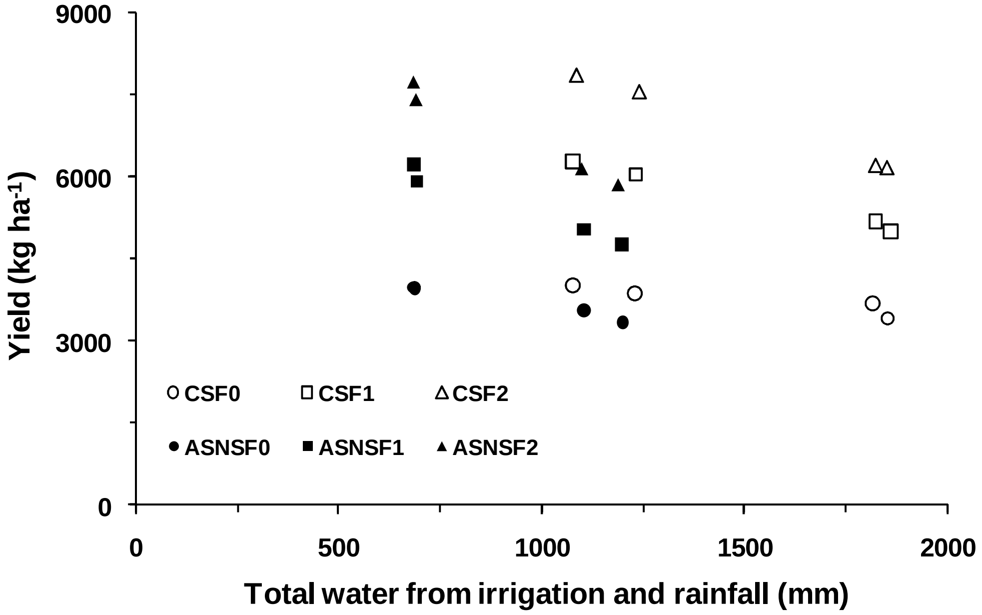

Figure 8.1 Variation in yield of rice over four seasons with total water used from rainfall and irrigation for various irrigation and fertilizer treatments.

The results of this experiment were comparable with the studies on fine textured soils with shallow ground water tables (Cabangon et al., 2004; Belder et al., 2004, Qi jing et al., 2007). The absence of any significant interaction in the effects of irrigation treatments with N-treatments suggest that these results may be considered as typical for well-drained fields with deep ground water tables in irrigated lowlands of eastern.

During the dry season after the harvest of the second rice crop, two types of legumes (soybean and peanut - commonly used as cash crop in this region) were planted to evaluate their performance in relation to the dynamics of N in soil as influenced by N-fertiliser application and any residual N remaining in soil from the previous crop (Chapter VI). Although nitrogen fertiliser application increased NH_4-N and NO_3-N concentrations in soil during legume growth, there was no significant effect of N fertiliser on growth, N-uptake and yield. Various studies have indicated inhibition to nodule formation in legumes with application of N fertiliser (Daimon et al. 1999; Taylor et al., 2005; Ray et al., 2006) including soybean (Starling et al., 1998) and peanut (Basu et al., 2008). The results of this study suggests that applying N fertiliser to peanut and soybean in rice-rice-legume crop sequence is unlikely to increase biomass and yield substantially. Thus, farmers in this region should not consider applying N fertiliser to peanut and soybean crops.

8.2 Nitrogen and carbon dynamics in rice-based cropping systems

In lowland rice-based cropping systems, there is an emphasis to maintain or improve rice yield with increased application of N-fertiliser. There are also concerns that in coarse textured soils, persistence of aerobic condition during rice crop, may reduce concentration of NH_4-N and increase the concentration of NO_3-N that may contribute to leaching losses and reduce N-uptake by the crop as rice crop prefers NH_4-N. From a modelling perspective, capturing the dynamics of various forms of N within ponded water and soil is a major challenge. Data on simulated NH_4-N over two rice seasons used for model validation are shown in Fig. 8.2 as an example of current limitation of the model to capture these dynamic aspects.

Measurements of NH_4-N and NO_3-N in Chapter V showed low concentration of NH_4- and NO_3-N with no added fertilizer-N (F0 treatment) which increased significantly with increased application of N fertiliser within 0-20 cm depth, but to a smaller extent at >20 cm depth. There were short periods of non-submergence in ASNS irrigation treatment that might have contributed to nitrification (Aulakh and Bijay-Singh, 1997) with higher levels of NO_3-N in ASNS than CS (during panicle initiation and flowering stages in some of the rice seasons). However, there was sufficient NH_4-N present in soil that did not adversely affect N-uptake by rice significantly. It appears that model deficiency in capturing the dynamic aspects of N-availability in soil and water during crop growth did not lead to poor performance of the model in predicting N-uptake of rice (Fig. 8.3).

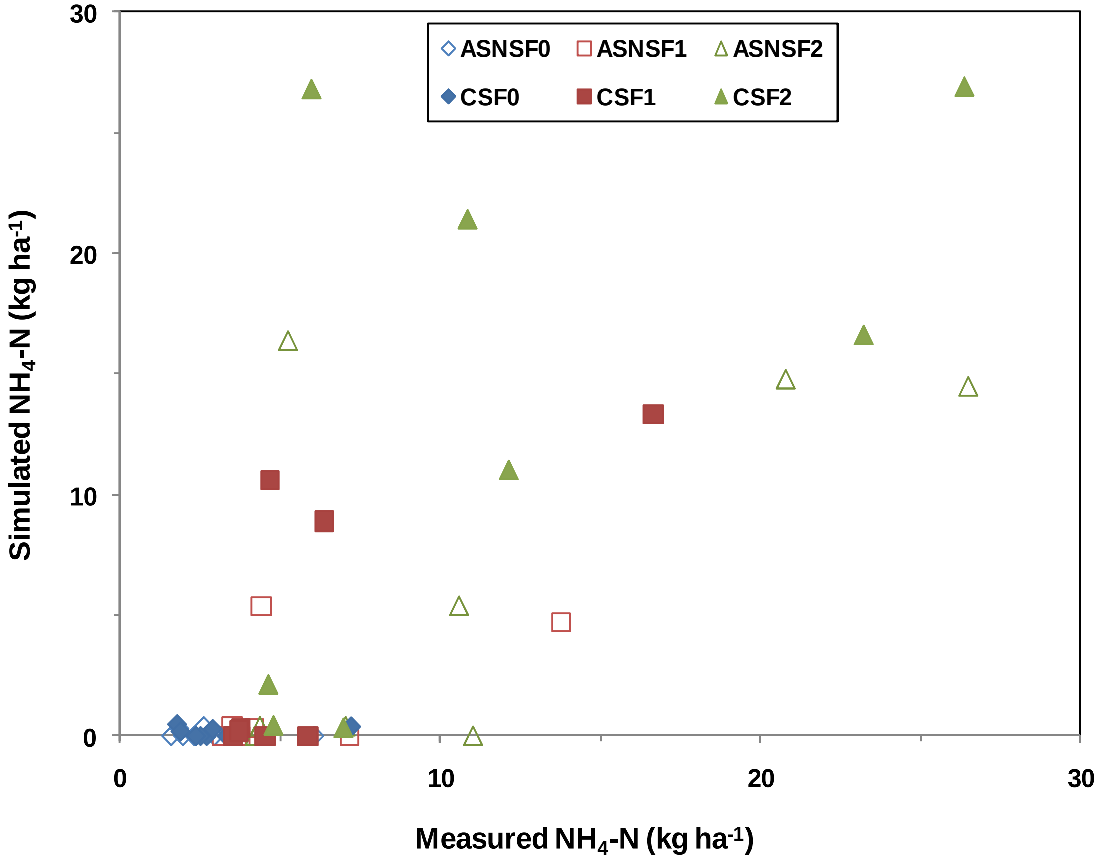

Figure 8.2 A comparison of simulated and measured concentration of NH_4-N within the top 20 cm of soil during the validation period of two rice seasons in 2008-09.

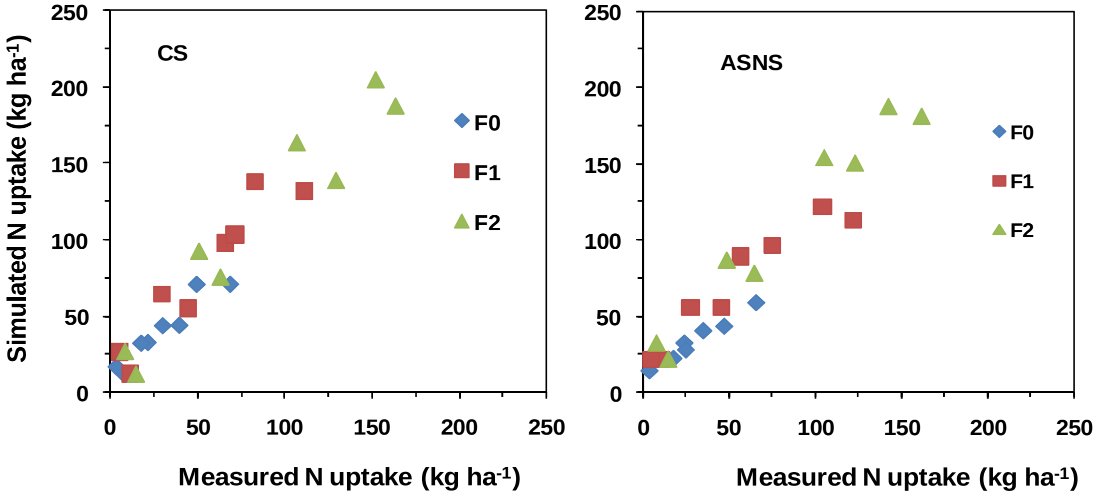

Figure 8.3 A comparison of simulated and measured N-uptake by rice for CS and ASNS treatments during the validation period of two rice seasons in 2008-2009.

During the growth of legumes, reasonable levels of NH_4- and NO_3-N were detected for the control plots that did not receive any fertiliser-N (F0 treatment). This may have occurred due to the mineralisation of organic matter as rice straw from the second rice crop was returned to the field for the legume season. For plots which received N-fertiliser, the concentration of NH_4-N and NO_3-N in soil increased with increased quantity of N fertiliser. On some occasions, high concentration of NO_3-N was found in deeper soil layers which would be prone to leaching losses during rain or irrigation. Although there was hardpan layer within 20-30 cm depth which may have contributed to reducing percolation rates, the soil at this experimental site was light texture i.e. sandy loam. Therefore, it is important to optimise N and irrigation management in cropping systems to reduce cost of fertilisers but also to avoid environmental pollution., .

8.3 Modelling rice-based cropping systems with APSIM-Oryza

Crop production and management strategies can change over time in a given region as they respond to decline in resources with or without climate change. Various adaptation strategies can be developed by using well-tested farming systems models as these can capture the complex interactions between water, nutrients, crop growth, climate variability and management practices. As mentioned previously, the alternation between anaerobic and aerobic conditions in rice and associated impacts on the decomposition of soil organic matter, nitrification and denitrification processes poses some challenge. Although APSIM is capable of modelling cropping systems, it was unequipped to describe the soil water, carbon and nitrogen dynamics for crops within a rotation that involved ponded rice and other non-ponded crops. Relevant chemical and biological processes that occur in long-term ponded fields were also not considered in APSIM. Gaydon et al. (2009) developed new elements in APSIM to capture these. In this study, the performance of the modified version of APSIM as APSIM-Oryza was used to simulate irrigated rice-rice-legume crop sequences under various nitrogen and irrigation treatments. Full details were considered in Chapter VII.

The overall performance of APSIM-Oryza indicated that the model was able to predict grain yield of rice over two seasons for both CS and ASNS water regimes and three rates of N-fertilizer application (Fig. 8.4). Results indicated that the model performed well in simulating the dynamics of daily floodwater during rice growth period for the CS irrigation treatment. However, APSIM-Oryza was unable to simulate the floodwater dynamics under ASNS on a daily basis, especially the occurrence of water level below the soil surface. Despite these, the simulated total water input (irrigation + rainfall) during the growing season was comparable with the measured values (Chapter VII).

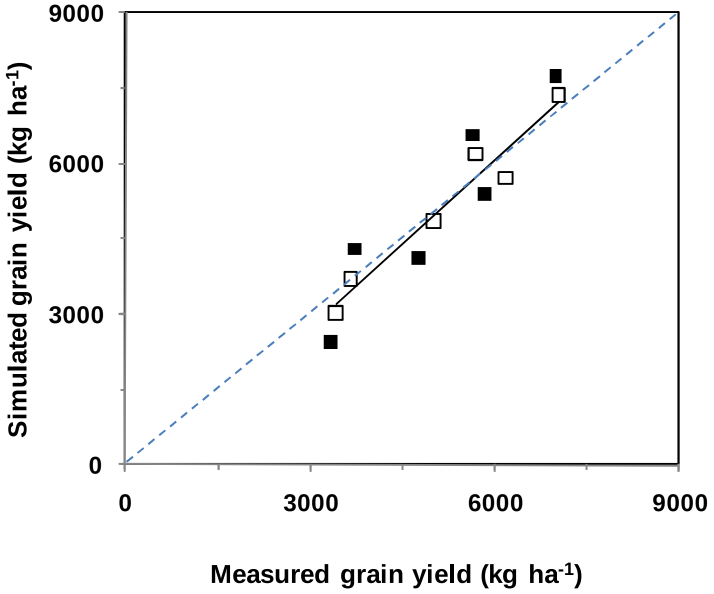

Figure 8.4 Simulated grain yield versus measured grain yield of rice over two seasons in 2008-09 used for model validation. Open and filled symbols denote data from CS and ASNS treatments, respectively. The solid line indicates the fitted regression line for the presented data and the dashed line represents the 1:1 line.

A new APSIM-Pond module is currently under development to simulate the dynamics of irrigated rice under ASNS water treatment or water limited conditions. This is an important development as maintenance of continuous submerged conditions in rice is difficult unless rainfall is well distributed over the growing season. As water is becoming scarce, it is important to develop farming systems that can adapt to reduced availability of water.

The APSIM-Oryza generally reproduced measured crop variables for rice and legumes. Simulated biomass, yield and LAI of rice and legumes were generally similar to measured values. Furthermore, the model was able to simulate N-uptake generally and match with measured values, although generally under-simulated of NH_4-N and NO_3-N concentration in soil.

The APSIM-Oryza was evaluated for soil variable with NH_4-N, NO_3-N and organic carbon (OC) under various N fertiliser and water treatments. The results showed that the model performed quite good in simulating the dynamic of soil organic carbon during rice and legume crops growth period. However, the model was generally poor in simulating NH_4-N and NO_3-N concentration of the soil during rice and legume crops growth periods under CS and ASNS water management and various N fertiliser application rates. Simulated NH_4-N and NO_3-N concentration in soil declined rapidly after a top dressing application of urea compared with higher measured values. Low values of simulated soil NO_3-N concentration suggested that the model is probably underestimating nitrification rate and/or overestimating denitrification. Furthermore, measured NO_3-N concentration in soil increased as soil depth increased which indicated that NO_3-N of soil has leached downward in this type of soil whereas simulated values were almost zero at deeper soil layers. This is probably because the APSIM was developed under a fine-textured soil on the assumption that soil oxygen is rapidly depleted under flooded conditions and all soil NO_3 denitrifies and disappears. However, this assumption may not be true for the coarse-textured soil with high percolation rates studied here where there was NH_4-N and NO_3-N concentrations in soil under anaerobic conditions although their absolute values were small (Fig. 8.1 and 8.2).

8.4 Conclusions

On the basis of the results presented in this work and implications discussed in this and other chapters, the following conclusions are reached.

- The absence of any significant reduction in yield, biomass and N-uptake in rice due to the direct effects of irrigation treatments and lack of significant interactive effects with N-treatments suggest that alternative submerged and non-submerged (ASNS) irrigation practices in lowland rice can save a considerable amount of water without affecting yield adversely. These results can be considered as typical for well-drained soils with deep ground water tables within the irrigated lowland rice producing region of eastern Indonesia.

- Due to the lack of any significant effects of N fertiliser rates on seed yield, harvest index, N-uptake and N-harvest index of both peanut and soybean, N-fertilizer should not be applied to legumes when it follows rice in this region. Thus, farmers can grow peanut and soybean in this region of study site without applying any N fertiliser.
- Frequent measurement of various available forms of N (NH_4-N and NO_3-N) during the growth of rice is required to develop an understanding of the net effects of various N-transformation processes in soil in anaerobic condition (under CS water regime) and aerobic condition (under ASNS water regime), plant uptake and losses from the root zone. During the growth of legumes, N-fixation with the formation of root nodules adds further complexity to these processes. A better understanding of these processes is required to improve water and nitrogen management strategies in rice-based farming systems to achieve sustainable yield while maintaining high nitrogen and water use efficiencies.
- The farming system model of APSIM-Oryza was successfully calibrated and validated for the experimental site. The model was able to capture the major effects of water and N-management strategies on crop functions that included growth and biomass, N-uptake and yield, but underestimated the dynamic aspects of NH_4-N and NO_3-N in soil, especially during alternation of anaerobic and aerobic conditions for lowland rice. Notwithstanding these minor limitations, APSIM-Oryza can be used to test and develop sustainable lowland rice-based farming systems to promote environmentally-friendly agricultural practices.

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APPENDIX 1. Logic commands for rice-rice legume crop sequences for APSIM-Oryza

Logic commands for rice-rice-legume crops sequence simulation in the general manager of APSIM are described below:

Rice crop

```
! SET MAX_POND =100 RIGHT AT START
'SOIL WATER' SET MAX_POND = 100

! ************** SOW RICE CROP LOGIC ******************************
! SOW FIRST RICE CROP IN NURSERY ON 6 NOV 2007, TRANSPLANT ON
23 NOV 2007
IF DAY = 311 AND YEAR = 2007 THEN
        RICE SOW CULTIVAR = CIGEULIS, ESTABLISHMENT =
TRANSPLANT, SBDUR = 17, NPLH = 1,  NH = 25   , NPLSB = 2000
     ENDIF

! SOW SECOND RICE CROP IN NURSERY ON 14 MAR 2008, TRANSPLANT
ON 2 APRIL 2008
IF DAY = 73 AND YEAR = 2008 THEN
       CROP = 2
        RICE SOW CULTIVAR = CIGEULIS, ESTABLISHMENT =
TRANSPLANT, SBDUR = 19, NPLH = 1,  NH = 25   , NPLSB = 2000
     ENDIF

! SOW THIRD RICE CROP IN NURSERY ON 15 NOV 2008, TRANSPLANT ON
2 DEC 2008
IF DAY = 320 AND YEAR = 2008 THEN
       CROP = 3
        RICE SOW CULTIVAR = CIGEULIS, ESTABLISHMENT =
TRANSPLANT, SBDUR = 17, NPLH = 1,  NH = 25   , NPLSB = 2000
     ENDIF

! SOW FOURTH RICE CROP IN NURSERY ON 13 MAR 2009, TRANSPLANT
ON 1 APR 2009
IF DAY = 72 AND YEAR = 2009 THEN
       CROP = 4
        RICE SOW CULTIVAR = CIGEULIS, ESTABLISHMENT =
TRANSPLANT, SBDUR = 19, NPLH = 1,  NH = 25   , NPLSB = 2000
     ENDIF


IF RICE.PLANT_STATUS = 'DEAD' THEN
      RICE END_CROP
     'SURFACE ORGANIC MATTER' TILLAGE TYPE = BURN_90
      TOT_IRRIG = 0
      IRRIG_AMOUNT = 0
     PONDED_DEPTH = 0
```

```
     IRRIGATION END
 ENDIF
```

Peanut crops

```
! ****NOW GROW A PEANUT CROP IN THIRD SEASON IN 2008 *********

IF DAY = 201 AND YEAR = 2008 THEN
  PEANUT SOW CULTIVAR = GARUDA, PLANTS = 15 (/M2),
SOWING_DEPTH = 40 (MM)
ENDIF

IF DAY = 230 AND YEAR = 2008 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF DAY = 240 AND YEAR = 2008 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF DAY = 250 AND YEAR = 2008 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF DAY = 260 AND YEAR = 2008 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF PEANUT.STAGENAME = 'HARVEST_RIPE' OR PEANUT.PLANT_STATUS
= 'DEAD' THEN
  PEANUT HARVEST
  PEANUT END_CROP
ENDIF!
***********************************************************

! *********NOW GROW A PEANUT CROP IN 3RD SEASON 2009 *********


IF DAY = 200 AND YEAR = 2009 THEN
  PEANUT SOW CULTIVAR = GARUDA, PLANTS = 15 (/M2),
SOWING_DEPTH = 40 (MM)
ENDIF

IF DAY = 220 AND YEAR = 2009 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF DAY = 230 AND YEAR = 2009 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF
```

```
IF DAY = 240 AND YEAR = 2009 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF DAY = 273 AND YEAR = 2009 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF PEANUT.STAGENAME = 'HARVEST_RIPE' OR PEANUT.PLANT_STATUS
= 'DEAD' THEN
  PEANUT HARVEST
  PEANUT END_CROP
ENDIF!
************************************************************
```

Soybean crop.

```
! ***** NOW GROW A SOYBEAN CROP IN THIRD SEASON IN 2008******

IF DAY = 199 AND YEAR = 2008 THEN
  SOYBEAN SOW CULTIVAR = WILIS, PLANTS = 15 (/M2),
SOWING_DEPTH = 40 (MM)
ENDIF

IF DAY = 230 AND YEAR = 2008 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF DAY = 240 AND YEAR = 2008 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF DAY = 250 AND YEAR = 2008 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF DAY = 260 AND YEAR = 2008 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF


IF SOYBEAN.STAGENAME = 'HARVEST_RIPE' OR
SOYBEAN.PLANT_STATUS = 'DEAD' THEN
  SOYBEAN HARVEST
  SOYBEAN END_CROP
ENDIF

! ****** NOW GROW A SOYBEAN CROP IN THIRD SEASON IN 2009******
```

```
IF DAY = 198 AND YEAR = 2009 THEN
  SOYBEAN SOW CULTIVAR = WILIS, PLANTS = 15 (/M2), SOWING_DEPTH = 40 (MM)
ENDIF

IF DAY = 220 AND YEAR = 2009 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF DAY = 230 AND YEAR = 2009 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF DAY = 240 AND YEAR = 2009 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF

IF DAY = 273 AND YEAR = 2009 THEN
  IRRIGATION APPLY AMOUNT = 30, NO3 = 3, NH4 = 0
ENDIF


IF DAY = 294 AND YEAR = 2009 THEN
  SOYBEAN HARVEST
  SOYBEAN END_CROP
ENDIF
```

Logic command for irrigation treatments as follow:

<u>For CS treatment:</u>

```
IF RICE.PLANT_STATUS = 'ALIVE' AND PONDED_DEPTH <= 15 AND RICE.DVS <= 1.75 AND RICE.DVS > 0.185 THEN
    IRRIG_AMOUNT = 100 - PONDED_DEPTH
  IF CROP = 1 THEN
      IRRIGATION APPLY AMOUNT = IRRIG_AMOUNT, NO3 = 2, NH4 = 0
      IF RICE.DVS >  0.2   THEN
          TOT_IRRIG = TOT_IRRIG + IRRIG_AMOUNT
      ENDIF
  ELSE
      IRRIGATION APPLY AMOUNT = IRRIG_AMOUNT, NO3 = 2, NH4 = 0
      IF RICE.DVS >  0.2   THEN
          TOT_IRRIG = TOT_IRRIG + IRRIG_AMOUNT
      ENDIF
   ENDIF
ENDIF
```

For ASNS treatment:

```
IF RICE.PLANT_STATUS = 'ALIVE' AND WATER_TABLE >=100 AND RICE.DVS > 0.185 THEN
   IRRIG_AMOUNT = 50
   IRRIGATION APPLY AMOUNT = IRRIG_AMOUNT
    IF RICE.DVS >  0.2   THEN
       TOT_IRRIG = TOT_IRRIG + IRRIG_AMOUNT
    ENDIF
ENDIF
```

<u>Logic command for fertiliser treatment as follow:</u>

```
! ************** RICE CROP 1 ****************************************
!  FERTILISE 7 DAYS AFTER TRANSPLANTING
 IF DAY = 334 AND YEAR = 2007 THEN
     FERTILISER APPLY AMOUNT = AMOUNT1, TYPE = UREA_N
  ENDIF

!  FERTILISE 29 DAYS AFTER TRANSPLANTING (TILLERING)
  IF DAY = 356 AND YEAR = 2007 THEN
     FERTILISER APPLY AMOUNT = AMOUNT2, TYPE = UREA_N
  ENDIF

IF DAY = 15 AND YEAR = 2008 THEN
     FERTILISER APPLY AMOUNT = AMOUNT3, TYPE = UREA_N
 ENDIF


! ************** RICE CROP 2 ****************************

IF DAY = 101 AND YEAR = 2008 THEN
     FERTILISER APPLY AMOUNT = AMOUNT1, TYPE = UREA_N
 ENDIF

 IF DAY = 123 AND YEAR = 2008 THEN
     FERTILISER APPLY AMOUNT = AMOUNT2, TYPE = UREA_N
  ENDIF

 IF DAY = 146 AND YEAR = 2008  THEN
     FERTILISER APPLY AMOUNT = AMOUNT3, TYPE = UREA_N
  ENDIF

! ************** RICE CROP 3 ****************************************

IF DAY = 344 AND YEAR = 2008 THEN
     FERTILISER APPLY AMOUNT = AMOUNT1, TYPE = UREA_N
 ENDIF

 IF DAY = 3 AND YEAR = 2009 THEN
     FERTILISER APPLY AMOUNT = AMOUNT2, TYPE = UREA_N
  ENDIF
```

```
 IF DAY = 22 AND YEAR = 2009  THEN
          FERTILISER APPLY AMOUNT = AMOUNT3, TYPE = UREA_N
   ENDIF

! ************** RICE CROP 4 *************************************

IF DAY = 99 AND YEAR = 2009 THEN
          FERTILISER APPLY AMOUNT = AMOUNT1, TYPE = UREA_N
  ENDIF

  IF DAY = 121 AND YEAR = 2009 THEN
          FERTILISER APPLY AMOUNT = AMOUNT2, TYPE = UREA_N
    ENDIF

 IF DAY = 144 AND YEAR = 2009  THEN
          FERTILISER APPLY AMOUNT = AMOUNT3, TYPE = UREA_N
   ENDIF

! ***************** PEANUT IN 2008**************************

!  FERTILISE 15 DAYS AFTER SOWING
  IF DAY = 215 AND YEAR = 2008 THEN
          FERTILISER APPLY AMOUNT = PNUT_AMOUNT1, TYPE = UREA_N
    ENDIF

!*********************************************************************

! ***************** PEANUT IN 2009***************************

!  FERTILISE 15 DAYS AFTER SOWING
  IF DAY = 215 AND YEAR = 2009 THEN
          FERTILISER APPLY AMOUNT = PNUT_AMOUNT1, TYPE = UREA_N
    ENDIF

! ***************** SOYBEAN IN 2008 *************************

!  FERTILISE 15 DAYS AFTER SOWING
  IF DAY = 215 AND YEAR = 2008 THEN
          FERTILISER APPLY AMOUNT = SOY_AMOUNT1, TYPE = UREA_N
    ENDIF

!  FERTILISE 40 DAYS AFTER SOWING
 IF DAY = 235 AND YEAR = 2008  THEN
          FERTILISER APPLY AMOUNT =  SOY_AMOUNT2, TYPE = UREA_N
   ENDIF

! ***************** SOYBEAN IN 2009 *************************

!  FERTILISE 15 DAYS AFTER SOWING
```

```
 IF DAY = 214 AND YEAR = 2009 THEN
      FERTILISER APPLY AMOUNT = SOY_AMOUNT1, TYPE = UREA_N
  ENDIF

!  FERTILISE 40 DAYS AFTER SOWING
 IF DAY = 235 AND YEAR = 2009  THEN
      FERTILISER APPLY AMOUNT =  SOY_AMOUNT2, TYPE = UREA_N
  ENDIF

!*****************************************************************
```