OPTIMIZING CULTURAL PRACTICES FOR SAVING WATER AND NITROGEN IN RICE- MAIZE CROPPING SYSTEM IN THE SEMI-ARID TROPICS

By

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To my parents, Ramana and Prakasa Rao

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The sustainability of traditional rice cultivation in many Asian countries is being questioned due to prevailing severe water shortage conditions necessitating the development of water-saving rice production technologies. A field experiment was conducted to compare traditional flooded rice-maize system with water saving aerobic rice-maize system, with the overall objective of studying water and nitrogen (N) balance in the both systems, using ^{15}N through field experimentation and simulation modeling. Adoption of aerobic rice method resulted in 37-45% of savings in water compared to flooded rice system. The aerobic rice system produced significantly lower grain yields and the differences between flooded and aerobic rice ranged from 15% to 39%. Significant increase in yields was recorded in both systems with increased N rates up to 120 kg ha^{-1}. The average fertilizer N recovery in aerobic rice was 26 kg per 100 kg of fertilizer N in the main field and 21 kg per 100 kg of N in the micro plot, while it was 41 and 32 kg ha^{-1} per 100 kg of N in flooded conditions. The fraction of ^{15}N that was found in soil after the harvest of rice crop ranged from 12 kg ha^{-1} to 45 kg ha^{-1} in aerobic rice and 14 kg ha^{-1} to 50 kg ha^{-1} in flooded rice. Nitrogen loss through leaching from flooded rice paddy was 4%, which is greater than the loss in the aerobic rice system (3%), while

N loss through weeds was <1% in aerobic system and 0.05% in flooded system. Average recovery of ^{15}N fertilizer in maize after the first growing season was 4% and the corresponding recovery in soil was 19%. An additional 1% of the fertilizer was recovered by crops during the two subsequent seasons. Significantly higher yields were obtained with no till maize grown after aerobic rice than the no-till maize after flooded rice. The results suggest that aerobic rice can be an option for water saving in rice. Yield and N use efficiency need to be improved to make aerobic rice cultivation more adoptable to the farmers.

CHAPTER 1
INTRODUCTION

Rice *(Oryza sativa* L.) is the world's most important food crop and a major source of food for more than one third of the world's population. The production of rice in South Asia, particularly in India has increased markedly with the introduction of nitrogen (N) -responsive semi-dwarf cultivars, greater use of inorganic N fertilizers, pesticides, farm mechanization and the expansion of irrigation facilities. Globally, rice is cultivated in 154 million hectares with an annual production of around 600 million tonnes and with an average productivity of 3.9 t ha^{-1}. In India, rice is cultivated round the year in diverse ecologies of rainfed upland, low land and irrigated conditions, spreading across 45 million hectares with a production of 99 million tons, with an average productivity of 2.2 t ha^{-1} (MOA, India, 2010). Rice-Rice is the dominant cropping system in assured irrigated regions of India and grown as a monoculture system with 2-3 crops per year depending on water availability. There are many areas in India, where during the dry periods instead of rice-rice rotation, rice-wheat, rice-maize and rice-pulse rotation systems are commonly practiced by the farmers.

Flooded rice is typically transplanted into the puddled soil and is grown under submerged conditions in 5-10 cm depth of standing water. Most of the water used for rice cultivation is lost through percolation, seepage and evaporation requiring more water than any other field crop. Decrease in availability of water for agriculture forced researchers and producers to look for alternate measures of rice cultivation to increase the productivity of water. Increasing water scarcity coupled with heavy demand for irrigation water for flooded crop emphasizes the need for shift to water-saving rice cultivation methods during rainy seasons, such as alternate wetting and drying (Tabbal et al., 2002), raised bed rice cultivation (Ockerby and Fukai, 2001) and aerobic rice (Bouman et al., 2005). The dry season rice should be replaced with maize- a potential high yielding crop under zero tillage, which provides an opportunity for improved resource use-efficiency, profitability and productivity of the system.

Nitrogen is the most important nutrient in rice-based production systems and contributes immensely to increased productivity. Nitrogen use efficiency in rice was reported to be very low, as it depends primarily on the time, method of fertilizer application and to a large extent, on water management. Many processes of the N cycle in rice cropping systems are influenced by the availability of water. Nitrogen dynamics in flooded rice fields are significantly different from that of water saving rice cultivation systems. Hence, knowledge of N transformations, fate of applied fertilizer N and losses in alternate rice water management systems is essential not only to reduce the N fertilizer cost but also to minimize the environmental impacts.

Crop simulation models synthesize various complex processes in soil-plant-atmosphere continuum and can be used as management tools to evaluate the production uncertainties associated with various management options (Timsina et al., 2006). Simulation studies using cropping system models with various water and N management strategies in rice based systems can assist in better decision- making on N use efficiency and also to study the residual N in crop sequence. These models also provide a means to upscale and to simulate different climates. Model evaluation and testing is important for identifying optimal water and nutrient management strategies under water saving rice based cropping systems.

In order to compare traditional flooded rice-maize (R-M) system with water saving aerobic R-M system, with an overall objective of determining water and N balance in the both systems, a two year field experiment using ^{15}N and simulation modeling was established at the ANGR Agricultural University research center with the following hypotheses: 1) Water productivity in R-M crop sequences can be increased without significantly decreasing the yield through improved water management systems such as aerobic rice, 2) A shift from continuously flooded to aerobic conditions may have profound effects on N balance in rice- maize cropping system, and 3) Simulation models such as DSSAT can be used to develop best management practices that reduces water use and maintain productivity for a sequence of crops.

The objectives of this study were to 1) study the effects of crop establishment methods and N rates on growth, yield and water productivity in rice, 2) determine the total recovery of applied inorganic N by the rice crop grown under aerobic and flooded rice systems and residual soil N by the subsequent crops, 3) calibrate and evaluate CERES-Rice and CERES-Maize models for soil water predictions, N balance and yields to develop the best management options to increase productivity of aerobic R-M system, and 4) predict rice yields, nutrient and moisture dynamics under alternate rice establishment methods at a watershed scale using CERES-Rice and GIS linkages.

CHAPTER 2
REVIEW OF LITERATURE

Rice Crop Establishment Methods

Crop establishment techniques and systems of cultivation have profound effect on the grain yields of rice. In the canal command areas, with the availability of resources for crop production especially labor and water becoming limited, due to high demand during peak transplanting season, disparities in optimum planting dates have become imminent. Under such situations, alternate methods of crop establishment and water management practices would be critical in safeguarding the economic returns to the rice growers.

Transplanted Rice

Transplanting is the typical method used for rice establishment and is considered to be superior to other establishment methods. The area under transplanted rice in the world is decreasing due to scarcity of labor and other resources. In irrigation command areas, rice is largely grown by transplanting seedlings in puddled soil conditions. It consumes approximately 25% of the total labor requirement of the crop (Chaudhary and Varshney, 2003). Transplanting also involves a lot of human drudgery. It has been reported that transplanting method of rice enhances the yield of long duration varieties when compared to broadcasting method of rice because transplanting reduces the excessive buildup of vegetative biomass due to transplanting shock (Himeda, 1994). The establishment of transplanted seedlings and their subsequent growth and development depends not only on the above ground morphological characteristics that define seedling vigour, but also on the growth of new roots and the root stress caused during transplanting (Ros et al., 2003).

Direct Seeded Rice / Aerobic Rice / Semi-Dry Rice

The direct seeded rice is characterized by planting of dry seed with the help of monsoon rains. Irrigation is given subsequently to keep the soil sufficiently moist by using tank, canal and ground water. Dry seeded rice enables advanced crop establishment to make use of early season rain water (Tuong, 1999). Direct seeding reduces labor requirement, shortens the crop duration by 7 – 10 days and can produce as much grain yield as that of a transplanted crop. Direct seeded rice needs only 34% of the total labor requirement and saves 29% of the total cost of the transplanted crop (Ho and Romil, 2000). Aerobic rice management eliminates water required for puddling and reduces water losses due to evaporation, percolation and thereby reduces the total irrigation requirements by 30 – 50% (Castaneda et al., 2004). Direct seeding of rice also allows early planting of succeeding crop due to decreased crop duration. Higher profit with short duration varieties under direct seeding can be achieved with assured water supply and efficient weed management (Balasubramanian and Hill, 2002).

Water Management in Rice

Rice Water Requirement

Water applied to flooded rice is lost mostly through seepage, evaporation, deep percolation and transpiration. Hence, water inputs to flooded rice fields should match the out flows. Land preparation for flooded rice consists of ploughing, soaking and puddling of the fields. The water requirement for puddling operations ranges between 150 and 200 mm and sometimes even goes up to 600-900 mm. Seepage and percolation losses are the major out flows from the rice field, ranging from 1 to 30 mm per day depending on the type of soil. These losses account for 25- 50% of the total water input in heavy soils (Cabangon et al., 2004; Dong et al., 2004) and 50-85% in coarse-textured soils (Sharma, 1989; Sharma et al., 2002; Singh et al., 2002). In rice fields, evapotranspiration losses include evaporation from ponded water and transpiration from rice plants and typically range between 6 and 7 mm per day. During the crop growth period, about 30–40% of evapotranspiration is estimated to be evaporation (Bouman et al., 2005; Simpson et al., 1992). As a result of the above losses, water requirement of low land rice varies from 1500 to 3000 mm (Balasubramanian and Krishnarajan, 2001; Tabbal et al., 2002; Choudhury et al., 2007). In other words, flooded rice requires approximately 1000 - 3000 m^3 of water to produce 1000 kg of rice (Wassmann et al., 2009).

Water Saving Aerobic Rice

Various water saving rice irrigation methods were developed to reduce water requirement of rice and aerobic rice is one such option. In this method, rice is grown like an upland crop under non-puddled, unsaturated soil without ponded water and water will be applied as when required to bring the soil water content to the field capacity (Bouman et al., 2005; Xiaoguang et al., 2005).

In majority of studies, it was observed that compared to lowland rice cultivation, the water used by aerobic rice was lower by more than 30-70% (Castaneda et al., 2004; Belder et al., 2005; Bouman et al., 2005; Reddy et al., 2010). Aerobic rice maximizes water use with regard to yield and is a suitable production technology under water shortage and water- costly conditions. On average, aerobic rice used 190 mm less water in land preparation and had 250-300 mm less seepage and percolation. The evaporation was 80 mm less and transpiration was 25 mm less compared to flooded fields (Bouman et al., 2005). In farmer’s fields of Northern China in 2001 at two different sites, the yield of aerobic rice varied from 4.5 to 6.5 t ha^{-1}, 20-30% lower than that of flooded condition but the water used was about 60% less. The total water productivity was 1.6 to 1.9 times higher and net returns to water use was two times higher than that of flooded rice. Aerobic rice required less labor than flooded rice and can be highly mechanized (Wang et al., 2002).

Experiments conducted in farmers' fields in Nueva province, Philippines, on water saving technologies in rice indicated that keeping the soil continuously around saturation resulted in 5% yield loss , 35% water input reduction and 45% increase in water productivity (Tabbal et al., 2002). In aerobic rice the irrigations are usually applied through flash flooding, though sometimes sprinklers are used. In an experiment conducted in Andhra Pradesh, India, on performance of aerobic rice under drip and sprinkler irrigation, Dakshina Murthy et al. (2006) observed that under aerobic rice, drip method of irrigation with 714 mm of water resulted in significantly higher grain yields (5208 kg ha^{-1}) compared to sprinkler method of irrigation with 920 mm of water (4092 kg ha^{-1}). In aerobic rice production system, continuous seepage, percolation and evaporation losses are greatly reduced and it effectively utilizes the rainfall enhancing the water productivity (Singh and Vishwanathan, 2006; Bouman et al., 2005). A study conducted at the Indian Agricultural Research Institute, New Delhi indicated that the lower water input in direct seeded rice kept at field capacity reduced the rate of evapotranspiration (22-31%) and percolation (22-38%) as compared to flooded transplanted crop (Choudhury et al., 2007).

Nitrogen in Rice

Nitrogen Requirement in Rice

Nitrogen is an important element in the soil and the biosphere (O'Hara et al., 2002). It is a very crucial and important nutrient required for rice crop growth, yield and in its absence, yields will be reduced drastically (Yoshida, 1981). Nitrogen in the soil is lost through leaching, runoff, denitrification and ammonia volatilization. All the detectable N loss from the flooded rice ecosystem occurred during the first 11 days after urea application mainly in gaseous form (Simpson et al., 1984). Long-term experiments conducted in rice on N requirements in Philippines and India revealed that N is the most limiting nutrient in irrigated rice systems and significant yield responses to applied N were observed in almost all types of soils (Nambiar and Ghosh, 1984; De Datta et al., 1988). Many field trials conducted in India indicated that rice requires 120 kg N ha^{-1}; however the exact requirement to get maximum yields depends up on the location, season and variety, among other factors. Rice varieties of medium to short duration utilize applied N during maximum tillering and flowering for grain production. The N absorbed during vegetative growth is stored and used during subsequent growth periods. Experimental results indicated that application of N in three split applications- one at transplanting, one at maximum tillering and another at panicle initiation- is the best management strategy for assuring higher yields.

Nitrogen Use Efficiency in Rice

Fertilizer use efficiency of N is relatively low in irrigated rice systems. Applied inorganic N is rapidly lost from the soil flood water mainly by volatilization and denitrification (De Datta and Buresh, 1989). In rice ecosystems, about 50% of the applied urea can be lost through ammonia volatilization and less than 10% is lost through gaseous form as denitrification (De Datta et al., 1991). The N use efficiency (NUE) of rice is very low and various methods were tried to increase NUE. However, the current NUE levels remain under 40% compared other upland crops. Most of the studies conducted in rice on recovery efficiency of fertilizer N in flooded rice system reported were in the 10 to 65% range (Table 2-1).

Nitrogen Transformation in Anaerobic and Aerobic Soils

Flooded rice soils are characterized by absence of oxygen in the system. The soil will have a specific zonation, an oxidized surface layer zone and an underlying reduced zone due to constant flooding of fields during rice growth (Reddy et al., 1984). In flooded rice with saturated anaerobic soils, N is available mostly in ammoniacal form because mineralization of organic matter will not proceed beyond ammonification due to lack of oxygen. The ammonium released will be either used by the plants or lost as gaseous form through ammonia volatilization and as denitrification in reduced layers (De Datta, 1981). In flooded soils nitrification generally occur in thin oxidized layer at the soil water interface. The nitrate produced may be absorbed by the plant or diffused to the soil below. Due to anaerobic conditions the diffused nitrate denitrifies biologically and is lost to atmosphere as N_2 gas. Under aerobic rice conditions soil is kept at near saturation and due to changes in the water regime, N transformation in the soil and N uptake by the plants will be affected. In aerobic rice system, the dominant form of N is nitrate and relatively lesser ammonia volatilization can be expected from fertilizer N application.

The effective utilization of N fertilizer in any system varies greatly with soil condition, method, time and form of fertilizer application (Prasad and De Datta, 1979; Craswell et al., 1981). A mixture of nitrate and ammoniacal form of N may result in better crop growth and N uptake in rice than the sole availability of NH_4^+ or NO_3^- (Ta et al., 1981; Qian et al., 2004).

Environmental Impacts of Water Saving Rice Cultivation

The traditional method of growing flooded rice uses high amounts of water and recent emphasis was on growing rice with increased water use efficiency. There is a need to critically review the benefits and drawbacks of growing rice under water saving aerobic rice, its impact on environment and on sustainability of rice cultivation. Flooded rice soil offers an ideal environment for accumulation of organic carbon (C) and N (Sahrawat, 2004[a]) compared to aerobic systems and makes them attractive for sequestration of C for increasing the fertility. Flooded soil is most suitable for aerobic and anaerobic microbial activity in its floodwater and contributes to higher net primary productivity (Reddy and Patrick, 1976). It also accelerates detoxification of certain pesticides which are known to persist in non-flooded soils and other aerobic systems (Sethunathan and Siddaramappa, 1978). Pesticide degradation is favored by reduced conditions, organic matter incorporation, as well as a pH, which in most flooded rice soils, stabilizes in a range favoring microbial activity (6.7 to 7.2) (Ponnamperuma, 1972). The decomposition of organic matter is relatively and comparatively slow, inefficient and incomplete under flooded or anaerobic soil conditions due to lack of electron acceptors compared to aerobic conditions. On the other hand, continuous submergence of soil promotes the production of methane (CH_4), an important greenhouse gas, due to anaerobic decomposition of organic matter. Flooded rice fields are considered one of the most important sources of atmospheric CH_4 and possibly an important source of N_2O. Reduced flooding duration increases N_2O production, whereas continuous flooding maintains anaerobic conditions and hence, enhances CH_4 production (Neue, 1993). Methane production rate is ordinarily high in flooded soils with high organic carbon content. Aerobic conditions maintain prolonged aeration of soil and can reduce methane emission but may result in increased emissions of nitrous oxide, another greenhouse gas. The toxic trace element arsenic (As) will have a rapid and marked mobilization as arsenate in the soil solution under flooded conditions (Xu et al., 2008). Bioavailability of As to rice is enhanced under flooded rice and growing rice under aerobic conditions can reduce the accumulation of As in rice plants. Water saving resulted due to adoption of water saving methods such as aerobic rice was mainly due to reduced drainage and percolation rates. The drainage and percolation outflows from flooded rice fields may go into drainage canals, recharge aquifers and play an environmentally important role in sustaining the fresh-saline water balance in estuaries and reducing the outflows may result in increased salinity intrusion (Tuong et al., 2004). Thus, proper understanding of the implications of water saving technologies will help in making an appropriate decision by considering trade-offs between water-saving , yields, and fertility maintenance for growing of an important crop such as rice (Sahrawat, 2004[b]).

Significance of Rice - Maize System

Rice-maize (R-M) system is gaining popularity mostly in India, Bangladesh, Pakistan and Nepal. In India, R-M systems are practiced mostly in Andhra Pradesh, Tamil Nadu, Karnataka and in the northeastern parts of India (Bihar and West Bengal) with acreage of more than 0.5 million hectares (Timsina et al., 2010). The entire eastern plains of Uttar Pradesh, India where the rice-wheat is the dominating system, is experiencing a decline in yield, particularly in wheat because of increasing threat of wild oats (*Phalaris minor*) and late harvest of rice. The delay in planting of wheat will result in very low temperatures at early growth, flowering and ripening periods reducing wheat yields. Winter maize in this context seems to be a vital and alternate crop to bridge productivity gap of rice-wheat cropping system (Sutaliya and Singh, 2005).

In Andhra Pradesh, India, rice-pulse is the dominating system. During the recent years, the pulse yields are declining due to salinity, weed infestation, pests and disease occurrence. Therefore, inclusion of maize in winter season under no till conditions after rice is gaining importance. The highest area under R-M system in India is in Andhra Pradesh where this system is rapidly increasing under resource-conserving technologies, mostly under zero tillage (Jat et al., 2009).

Effect of Rice Crop Establishment Methods on Rice Based Systems

In the traditional flooded rice method of establishment, the fields are usually dry ploughed, flooded, and then puddled to create a soil with poor soil physical properties and low water infiltration. Puddling followed in rice will destroy the soil structure and will have influence on the growth of succeeding crop. Further, too wet conditions after harvest of rice delay land preparation and timely planting of succeeding crop resulting in poor yields. Water saving rice establishment methods such as direct seeding and raised bed planting in rice and zero tillage practices in wheat that showed beneficial results in the Indo-Gangetic regions need to be followed in the new emerging R-M systems also. Tripathi et al. (1999) conducted an experiment on evaluation of zero-tillage in wheat under different methods of rice establishment during 1993-94 and 1994-95 indicated that transplanting of rice recorded 14% higher yields compared to dry seeding of rice during monsoon season. On the other hand, no tillage wheat planted after rice in direct seeded plots recorded significantly higher grain yield than that after transplanted rice due to more 1000 grain weight and grains per spike with a saving of 16% on cost of cultivation. The total productivity of rice-wheat system was similar irrespective of establishment method for rice.

At Pantnagar, India on silt loam soils, direct seeded rice on non-puddled soils gave similar yields as that of transplanted rice (Hobbs et al. 2000). Wheat yield was significantly higher in plots where soil was not puddled and yield advantage varied from 9% to 14% mainly due to higher spikes m^{-2}, grains per spike and 1000-grain weight. Contrary to the above, Samra and Dhillon (2000) from Ludhiana, India reported that the wheat grain yield was not influenced significantly by different methods of crop establishment of previous rice crop.

The results from 3-year field studies in Uttaranchal, India showed no differences between yields of rice grown under transplanted and direct planted conditions. However, in the following season, wheat yield was higher in plots where rice was directly planted because of adverse effects of puddling on the following wheat crop (Singh et al., 2002). The yield gain in wheat was 4% higher in zero-tilled plots compared to that in the conventionally tilled plots. The rice-wheat system responded up to 150% of recommended fertilizer rate.

At Modipuram, India, the succeeding wheat crop recorded higher yields under unpuddled condition than under transplanted condition. Similarly, unpuddled rice-wheat system gave similar rice equivalent yield to that of transplanted rice-wheat system (Sharma et al., 2005).

The wheat crop planted after puddled rice plot resulted in lowest grain yield as compared to that under unpuddled direct planted rice plot (Singh et al., 2008). This could be attributed to restricted wheat root system and its proliferation to deeper layers of soil after rice. Unpuddled conditions, in turn, reduced the soil volume for exploring soil nutrients and moisture from deeper profiles, resulting in lower grain yields in wheat. The rice established in puddled soil depleted higher amount of N, P and K as compared to rice established in unpuddled plot. Similar results were also reported by Parihar (2004) in rice-wheat system.

Chandrapala et al. (2010) reported that significantly higher mean cob weight (229 g), grains cob^{-1} (246) and 100 seed weight (23.2 g) were recorded in maize grown after rice in conventional transplanted rice plots under zero-tilled conditions compared to maize grown in direct seeded rice plot under puddled condition in R-M system.

Crop Modeling

Nitrogen transformations in puddled submerged rice fields and alternate water saving aerobic rice fields are quite different and it is very difficult to accurately assess the effects of applied N and associated losses in both the systems. Although some of these losses of N can be measured with extensive sampling and measurements but the resultant costs are high and labor intensive. Crop simulation modeling is one of the options in such situations for the analysis of system performance under different alternate water saving technologies and to monitor their effects on succeeding crops. Crop models can potentially be used to study the bio-physical processes in the plant–soil–atmosphere system, the uncertainties in various management options, and to identify the factors with the greatest impact on yield potential (Aggarwal et al., 1997; Timsina and Humphreys, 2006). There are many models available to simulate crops independently but very few models are capable of simulating crop sequences. Cropping system models have the ability to simulate the effect of one specific crop on soil, water, and nutrient status that carries to the succeeding crop and allow simulations of cropping systems over a wide range of environments and management practices (Thornton et al., 1994), thus making crop models a valuable tool in agricultural production.

Rice Crop Models

Development of crop models to simulate rice growth and development was started more than thirty five years ago. A large numbers of models developed to study rice growth and yields include CERES-Rice (Godwin and Singh ,1991, 1998), ORYZA1 (Kropff et al., 1994), The Temperate Rice Yield Crop Growth model (Williams et al., 1994), Very Simple Model -VSM (Kobayashi, 1994), Simulation Model for Rice-Weather Relations -SIMRIW (Horie et al., 1992), Rice Growth Calendar Simulation model (Yin and Qi, 1994), Rice-Weed Competition model (Graf et al.,1990) and ORYZA2000 (Bouman et al., 2001). Each model has its own advantages, disadvantages, data requirements, underlying assumptions and complexity.

CERES-Rice Model

CERES-Rice model, a part of the DSSAT (Decision Support System for Agricultural Technology) suite of models, is a process oriented, management level model that will simulate rice crop growth, development and yield taking into account the effects of weather, management, genetics, soil water, C and N. (Jones et al., 2003). There are many studies that were reported on calibration and evaluation of this model across the globe. The Rice model considers soil water conditions, crop management and the cultivars as important factors in determining the rice productivity. The input data required for this model are the crop management data, daily precipitation, maximum and minimum temperature, and solar radiation for simulation.

Oryza 2000

Oryza 2000 is the latest development in ORYZA series of models viz., ORYZA1 for potential production (Kropff et al., 1994), ORYZA_W for water-limited production (Wopereis et al., 1996), ORYZA-N for N-limited production (Drenth et al., 1994) and was released during 2001 (Bowman et al., 2001). The model has the capacity to simulate the situations of potential production, water limitations, and N limitations. The main limitation for this model, however, is that it cannot simulate cropping systems and may not be of use to study the residual effect of soil N and water for the subsequent crops.

Cropping System Models

Cropping system models will aid as analytical tools to study the effect of climate, soils, and management on cropping systems, productivity and the environment. The models which are capable of simulating crop rotations are needed for the analysis of cropping systems. The CropSyst and models available within DSSAT are capable of simulating crop rotations. CropSyst is a multiyear, multi crop and a daily time step crop growth simulation model developed with an emphasis on a friendly user interface linked to GIS and weather generator software (Stockle et al., 2003). The DSSAT is the most widely known and used dynamic simulation model applied to agricultural production. The cropping system model (CSM) in DSSAT is a well-developed process-oriented model capable of simulating long term rotation experiments (Tsuji et al., 1994; Jones et al., 2003). Each crop in the rotation has a separate module, which simulates growth and development. The seasonal and sequence analysis components of DSSAT will assist in simulating long-term cropping systems with climate variability, decision making among various management options, carbon sequestration and long term yield forecasting (Porter et al., 2009). The CERES-Rice model was evaluated by many researchers across locations for crop growth and yield (Ritchie et al., 1998; Singh et al., 1999; Sarkar and Kar, 2006; Timsina and Humphreys, 2006) and observed good fit between predicted and observed values. Some studies using these simulation models were taken up to increase resource use efficiency of cropping systems (Timsina and Connor, 2001; Sarkar and Kar, 2006; Timsina and Humphreys, 2006). All the models are revised regularly for enhancing the accuracy. Simulation of various crop and fertilizer management strategies using such models can lead to development of best management practices for the emerging cropping systems such as R-M.

Conclusions

There is a growing concern about overexploitation of ground water for rice cultivation under traditional flooded method. Research on water-saving rice cultivation practices need to be intensified to produce stable yields comparable to flooded rice. Rice followed by maize is one of the most important cropping systems for food security in South Asia. The nutrient demand for this system is very high as both rice and maize are nutrient intensive crops. Hence, studies on nutrient balances in the R-M systems are very essential especially under alternate rice establishment methods. Increased N use efficiency and water productivity should be the main criteria in developing optimum water and N management practices for R-M systems.

Table 2-1. Nitrogen use efficiency of rice observed in various studies conducted in different countries.

S. No	Country	N Use efficiency	Source
1	USA	33.0-61.0%	Reddy and Patrick Jr.,1976
		30.2-47.6%	Westcott et al., 1986
		16.1-61.0%	Norman et al., 1989
		45.0-46.0%	Bronson et al., 2000
2	Philippines	39.0%	De Datta et al.,1987
		20.0-47.0%	De Datta et al., 1988
		29.0-40.0%	John et al., 1989
		36.0%	Belder et al., 2005
3	India	18.0-38.0%	Khind and Datta,1975
		18.6%	Shinde et al., 1985
		31.0-44.0%	Panda et al., 1995
		34.0-37.7%	Singh et al., 2001
4	China	23.3- 30.3%	Wang et al., 2008
5	Thailand	8.0-42%	Koyama et al.,1973
6	Japan	7.0-63%	Murayama,1979
7	Sri Lanka	29.2-55.9%	Nagarajah et al.,1975

CHAPTER 3
IMPACT OF AEROBIC RICE CULTIVATION ON GROWTH, YIELD AND WATER PRODUCTIVITY OF RICE-MAIZE ROTATION IN SEMI-ARID-TROPICS

Background

Rice (Oryza sativa L.) is an important staple food crop around the world. In Asia, the flooded rice production is a key element for economic and social stability as more than two billion people depend on rice cultivation. Rice production involves submerged conditions, with approximately 5-10 cm deep standing water throughout the crop growth period. Worldwide rice production utilizes about 30% of all freshwater and more than 45% of total fresh water in Asia (Barker et al., 1999). Increasing water scarcity due to increasing demand from various sectors threatens the sustainability of irrigated rice production and calls for development of novel technologies that can reduce water requirement without experiencing yield losses. Since 1990's, traditional flooded rice cultivation has increasingly experienced shortages in irrigation water, labor force and higher labor wages. These factors have adversely impacted farm operations. Puddling is a pre-requisite for flooded rice, however it deteriorates soil structure; therefore, land preparation for the succeeding crops becomes difficult and requires more energy to attain proper soil tilth. These conditions emphasize the need for shift to water saving rice cultivation methods, which can reduce labor requirement, save 20-30% of irrigation water, shorten the duration of crop and produce comparable grain yields.

Rice crop is very sensitive to water stress and reduction in water inputs can result in decline of yield (Tuong et al., 2004). Researchers developed several technologies to reduce water inputs in rice such as alternate wetting and drying (Tabbal et al., 2002), raised bed rice cultivation (Ockerby and Fukai, 2001), saturated soil culture (Borrell et al., 1997), system of rice intensification (Stoop et al., 2002), ground cover systems (Lin et al., 2002) and raised bed systems (Choudhury et al.,2007). Some of these technologies also require puddling and ponded water during crop growth and hence significant water saving was not always reported. Aerobic rice offers one such water saving rice technology (Bouman et al., 2005), where rice crop is cultivated under non-puddled and non-saturated soils. This concept is mainly is targeted for irrigated lowlands, where water is not sufficient for rice cultivation and favorable uplands, where facilities for supplemental irrigation are available (Belder et al., 2005). Earlier experimental studies reported aerobic rice yields up to 6.5 t ha^{-1} with 40- 60% water savings (Castaneda et al., 2002; Belder et al., 2005; Bouman et al., 2005). But such studies were limited to few parts of the world, without giving much consideration to the prospects of aerobic rice cultivation in the Indian subcontinent. Exact quantification of water balance and suitability of high yielding flooded rice varieties under aerobic system needs to be evaluated. Rice-maize (R-M) system is gaining popularity mostly in India, Bangladesh, Pakistan and Nepal as an important alternate crop to bridge productivity gap of rice-wheat cropping system. Crops grown after flooded rice will suffer with poor growth due to altered soil physical and nutrient relations due to anaerobic and aerobic transitions. Growing rice aerobically without puddling may have positive implications on succeeding maze (Chandrapala et al., 2010). Little information is available on impacts of aerobic rice cultivation on succeeding maize crop growth and overall system water balance and yields. Hence a field study was conducted with the objective to determine the effect of aerobic rice cultivation (I) on growth and yield, and (ii) on water use and water productivity, of rice and of succeeding maize crop.

Materials and Methods

Site Description

A field experiment was conducted over two consecutive years (2009-10 and 2010-11) on a rice-maize cropping sequence at the Acharya NG Ranga Agricultural University Research Station, Hyderabad (17°19’ N, 78°28’ E and 534 m above mean sea level), India. The region has a semi-arid climate and receives an annual rainfall of 850 mm, 80% of which occurs during south west monsoon period (June- October) (Figure 3-1). The soil at the experimental site has a sandy loam texture and had a pH of 8.0 in the surface 0-15 cm depth. Soil test results showed that phosphorus (P) was high but had low potassium (K). The soil was found to be low in $KMnO_4$ extractable N. Weather parameters such as the maximum and minimum air temperature, bright sunshine hours, and rainfall were measured during the crop growth at the meteorological observatory located on the research station.

Experimental Design and Treatments

The experiment was laid out with three replications in a split plot design with methods of rice establishment viz., aerobic and conventional flooded method as main treatments and four N rates as sub plot treatments (0, 60 120 and 180 kg N ha^{-1}). The aerobic plots were dry ploughed, harrowed and left unpuddled during land preparation. A popular low land variety, Cotton Dora Sannalu (MTU 1010) was used in this experiment because of its good performance under aerobic conditions. Seeds were hand dibbled in rows at 22.5 cm spacing with a seed rate of 300 seeds m^{-2}. Planting was followed by pre-emergence herbicide application of pendimethalin at one kg active ingredient ha^{-1}. Manual hand weeding was done at 30 and 45 days after planting (DAP). Aerobic plots were flood irrigated with 5 cm water when the soil moisture tension at the surface 15 cm depth reached -30 kPa during the crop period. There was no ponded water except for parts of the days when irrigation occurred or when a heavy rain was received. Flooded plots were puddled using tractor drawn cage wheel and kept continuously flooded from transplanting until one week before harvest. Transplanting using 30 day old seedlings, raised separately in the nursery was done at a spacing of 20 x 15 cm. Water depth was initially maintained at 2 cm and gradually increased to 5 cm at full crop development. Both aerobic and flooded rice were planted on the same day. The rice crop in both systems received 26 kg P and 33 kg K ha^{-1}. Both P and K fertilizers were applied as basal while N was applied according to the treatments in three splits- at the time of planting/ transplanting, active tillering and panicle initiation stages. The aerobic and flooded plots were separated by a set of drains that were one meter wide and 40 cm deep between the main plots and 75 cm wide and 30 cm deep between the subplots. Plastic sheets were installed to a depth of 40 cm in the channels between the main plots to prevent any seepage. Irrigation water was distributed to each plot using HDPE pipes installed with water meters to measure the amounts of water applied. After rice harvest, DeKalb 800 M variety of maize was planted at a spacing of 60 x 20 cm under no-till conditions. The maize crop received 120 kg N, 26 kg P and 33 kg K ha^{-1}. Both P and K fertilizers were applied as basal while N was applied in three splits- at the time of planting, knee-height stage and at silking. The crop was irrigated with 50 mm water, which is scheduled at IW/CPE (irrigation water/cumulative pan evaporation ratio) of 1.0.

Measurements

Growth analysis

Plant samples from a 0.50 m^2 area from flooded treatments at 30, 60 days after transplanting (DAT) and at harvest. Similarly in aerobic plots, plant samples were collected from a 0.50 m^2 area but at 30, 60, 90 DAS and at harvest growth analysis. Leaf area index (LAI) was measured with LI-3100 area meter (LICOR-Lincoln, Nebraska) for all samples. Dry matter was estimated after oven-drying at 60^o C to constant weight. Plants from 1.0 m^2 were sampled from harvest area to determine the aboveground total biomass and the yield components. Number of panicles for each plant within 1.0 m^2 was counted. Plants were separated into straw and panicles. Straw dry weight was determined after oven drying at 60^o C to a constant weight. Panicles were threshed by hand and filled spikelets were separated from unfilled by submerging them in 1.06 specific gravity salt solution. Number of filled spikelet per panicle and 1000 grain weight were calculated. Grain yield was determined from a net plot area of 49 m^2 leaving boarder rows and was expressed at 14% moisture content. In Maize, crop growth parameters such as LAI, above-ground plant biomass, yield components and final yield were also similarly recorded. Tissue total N concentrations were determined by using micro-Kjeldahl digestion (Bremner, 1965) method.

Suction lysimeters were installed vertically to depth of 45 cm to collect soil pore water samples. A suction lysimeter consisted of a porous cup attached to a polyvinyl chloride (PVC) pipe, which allowed the water in the cup to be pumped out. The percolation water in flooded treatments was sampled for 10 days during the rice season with a vacuum pump, while for aerobic rice plots samples were collected after heavy rainfall events.

Water balance

The water balance of rice was calculated as

$$IR + E\ R = DP + ET + \Delta W \tag{3-1}$$

where IR is the irrigation, ER is the effective rainfall computed from rainfall data (R), ET is the evapotranspiration, DP is the percolation below the root zone and ΔW is the change in soil water storage in the root zone. The IR and the R were directly measured from the inputs. Six access tubes were installed in a grid pattern in aerobic plots. The volumetric water content (VWC) was measured using Delta-T Devices theta probe with a PR2 sensor, a multi-sensor capacitance probe. The probe was initially calibrated with gravimetric method. The VWC were measured at each depth increment (10, 20, 30, and 60) in each access tube at weekly intervals and between two irrigations. The directly measured VWC was converted to millimeters of water by multiplying with the corresponding soil depth.

Irrigation (I)

The amount of irrigation water applied was directly measured using water meter connected to the distribution pipes later converted to depth of water (mm).

Change in stored soil water content (ΔW)

The change in stored soil water was determined as the difference in volumetric soil water content in the root zone before each subsequent irrigation from the capacitance probe readings. Estimates of stored soil water were the mean of measurements taken from six access tubes, which were converted to depth of soil water (mm).

Crop evapotranspiration (ET)

ET in aerobic rice was calculated by determining the reference crop evapotranspiration (ET_0) using Penman-Monteith method and multiplying with the appropriate crop coefficient based on the crop growth stages.

Finally, deep percolation was calculated for each irrigation (by the difference between inflows and outflows) and was cumulated to get an estimate for the entire season. To measure deep percolation in flooded rice, four pairs of PVC pipes of 25 cm diameter, 0.10 cm wall thickness and 60 cm height were used as lysimeters. Each pair included one open top and a close-ended bottom. Lysimeters were installed prior to transplanting by digging the soil to a depth of 45 cm. The soil was carefully replaced in the same order of layering minimizing disturbance to the soil within the lysimeters. Water was added to the lysimeters to establish equivalent water levels inside and outside the lysimeters. Water was added to the lysimeters thrice a week to maintain the water levels. Deep percolation was calculated as the difference in water additions to the sealed and unsealed lysimeters. ET was calculated as the remainder from the Eq. (3-1) and was found to be comparable to the water added to the sealed lysimeters. In maize IR and R were directly measured. ET was calculated by determining the ET_0 and adjusting it with crop coefficients. The ΔW was calculated from difference in measured soil water contents between maize planting and harvest using theta probe and DP was calculate as the remainder using Eq. (3-1).

Water productivity

Water productivity (WP) (g grain kg^{-1} of water) was calculated for rice and maize by following Eq. (3-2).

$$WP = \frac{Y}{WA_{(IR+R)}} \qquad (3\text{-}2)$$

Y= yield (kg ha^{-1}) WA = Total water input (IR+R)

Statistical Analysis

Yield and yield attributes of rice and maize, N uptake were analyzed with IRRISTAT for windows(Bartolome et al., 1999), which consisted of analysis of variance (ANOVA), with rice establishment method and N rates as main and sub factors, respectively. Whenever the treatments were found significant, pair-wise testing with t-test was done between the main and subplot treatments at 95% confidence interval.

Results

The mean monthly maximum temperature during cropping period (June to April) ranged from 28.2 to 40.3^{o} C and 27.8 to 36.7^{o} C in 2009-10 and 2010-11, respectively (Figure 3-1). The weekly mean minimum temperature varied from 14.1 to 24.8^{o} C and 10.4 to 24.7^{o} C during the same period. Rainfall of 652 mm was received in 36 rainy days and 1002 mm in 62 rainy days during 2009-10 and 2010-11, respectively. The rainfall received during the year 2009 crop season was 24% less and was 17% excess in 2010 compared to decennial averages from the weather records at the research station. The monthly mean bright sunshine hours per day ranged from 4.2 to 8.8 hours during 2009-10 and 2.5 to 8.9 hours during 2010-11.

Water Balance

Water balance estimates and its components are given in Table 3-1. Total irrigation input in flooded plots including land preparation was 1214 mm in 2009 and 740 mm in 2010, whereas the total irrigation input in aerobic rice was 625mm and 0 mm in 2009 and 2010 respectively, resulting in water savings of 589 and 740 mm in the first and the second year, compared to flooded method Irrigations were not applied to aerobic rice during 2010 due to adequate and well distributed rainfall (Fig. 3-1). The average daily deep percolation rates were 2.2 to 3.7 mm in aerobic plots compared to 6.8 to 7.2 mm in flooded plots. The overall deep percolation losses in aerobic plots were 237 mm and 377 mm lesser than flooded plots during 2009 and 2010 respectively. Daily average ET losses under aerobic conditions ranged from 3.2 to 3.7 mm compared to 3.9 to 4.3 mm in flooded plots during both the years of study. The lower evaporation values in aerobic plots compared to flooded plots were due to lower evaporation rates from dry aerobic soil and lesser leaf area values in aerobic plots. Include flooded soils and higher E and T. Because of lower deep percolation and ET rates, water application efficiency (total water input/ET*100) was higher in the aerobic plots (45% and 57%), compared to flooded method (26.4% and 30%). in 2009 and 2010, respectively).

In year 2009, soil moisture content at 10 cm was maintained at an average 0.25 cm^3 $cm^{-3,}$ within a range of 0.20 to 0.31 cm^3 cm^{-3} across entire crop field was (Figure 3-2). This indicated that the negative potential in the surface 10 cm was generally at the field capacity. However, soil at 20 and 30 cm depth was much wetter and the matric potential ranged between -33 and -10 kPa (equivalent to 0.30-0.35 cm^3 cm^{-3}). In year 2010, due to high and well distributed rainfall, the surface soil up to 10 cm depth generally remained between -33 and -10 kPa throughout the growing period of aerobic rice.

The subsequent maize grown in the flooded rice plots received relatively lower amounts of irrigation water, typically by 10 and 40 mm during 2010 and 2011, respectively, compared to aerobic R-M plots. Lower ET values were found in aerobic plots planted to maize. However, the differences in irrigation water and ET were small between the rice establishment methods and may be attributed to the delay in planting of flooded R-M crop.

Water Productivity

Flooded rice treatment used 1546 and 1181 mm of water (includes water applied for puddling) compared to aerobic rice (967 and 645 mm) during 2009 and 2010, respectively (Table 3-2). Despite the lower water use under aerobic rice, water productivity remained suppressed due to lower yields in 2009. However, in 2010 due to high rainfall and associated improved yields in aerobic rice, the water productivity was 55% higher than in flooded rice. In the succeeding maize crop, overall water productivity was 3-4 times higher than the rice water productivity across both methods. During the year 2009, we found that the water productivity of maize after aerobic rice was higher while in 2010 maize followed by flood rice showed significantly higher water productivity. Lowest water use and highest water productivity (0.66 and 1.05) were found under aerobic R-M system compared to flooded R-M (0.54 and 0.73) system during both the years of the study. The water productivity of R-M system was 22-44% higher than that of flooded R-M system during 2009 and 2010, respectively.

Crop Growth and Development

During initial crop growth period (up to 60 DAS), dry matter production was found to be lower in flooded method (30 DAT) of crop establishment whereas at subsequent periods, the flooded method recorded significantly higher dry matter production compared to aerobic method during both years (Figure 3-3). Dry matter production at harvest (average of four N rates) was the highest in flooded rice (1082 g m^{-2} and 1065 g m^{-2}) compared to aerobic rice (693 g m^{-2} and 957 g m^{-2}) during 2009 and 2010, respectively. Nitrogen rates significantly influenced dry matter accumulation of rice grown under both establishment methods. This may be attributed to the availability of N as per crop needs during its growth. The N application rate of 180 kg ha^{-1} produced maximum dry matter at physiological maturity and was significantly superior to lower N rates.

The LAI values showed typical pattern overtime with highest values during heading (90 DAS) followed by a decreasing trend until maturity in both the years and establishment methods (Figure 3-4). Between the two establishment methods, significantly higher LAI was observed in flooded method at all the growth stages. The LAI was significantly higher at heading stage (90 DAS) under flooded method (3.29 in 2009 and 3.32 in 2010) over aerobic method (2.22 in 2009 and 3.11 in 2010). Lower LAI values in aerobic plots were associated with reduced total biomass and grain yield at the end of the growing season. Temporal curves of LAI indicated that increased application of N from 0 to 180 kg N ha^{-1} had increased LAI of rice under both systems.

Rice Yield Attributes and Yield

Rice crop establishment methods showed significant influence on all the yield attributes during both years of study. Higher value of panicles m^{-2}, spikelet number per panicle and 1000 grain weight were observed during the second year than in the first year under aerobic rice. Although aerobic method had significantly higher panicles m^{-2}; the other yield attributing characters such as spikelet number per panicle and 1000-grain weight were significantly higher in flooded method (Table 3-3). All yield associated characters were found to be lower in aerobic conditions compared to flooded conditions. This effect was particularly pronounced during the year 2009. This indicated that aerobic rice may have suffered water and N stress around panicle initiation stage to maturity causing reduction in grain number and individual grain filling.

Production of panicles m^{-2} under different N rates varied from 230 and 184 with 0 kg N in flooded system to 388 and 367 with aerobic rice treatment receiving 180 kg N ha^{-1} during 2009 and 2010, respectively. There was a general increase in panicle production with increased N application. The other yield attributing characters such as spikelet number per panicle and 1000-grain weight showed similar trend to increased rates of N. In general, response to incremental rates of N was more pronounced in flooded conditions than aerobic rice treatments.

Grain yields in aerobic rice plots were significantly lower than yields in flooded rice. Highest yields were obtained with flooded rice receiving 180 kg N ha^{-1} in both years but the yields were similar during 2009 at 120 kg N ha^{-1}. The increase in yield under flooded method was 39.0% and 15.4% higher over aerobic method during 1st and 2nd years, respectively. Grain yields responded strongly to N fertilization for both years, in both aerobic and flooded rice treatments (Figures 3-8, 3-9). Response to applied N was more conspicuous in flooded rice compared to aerobic rice. Mean yield increase across both the years was 32%, 77% and 96% in aerobic rice and 41%, 94% and 112% in flooded rice at the 60, 120 and 180 kg N ha^{-1} application rates compared to no N application.

Nitrogen Uptake

Nitrogen uptake in rice plants showed significant differences at all sampling events among different N rates under both systems (Figure 3-5). The highest N uptake in rice was recorded at the 180 kg N ha^{-1} rate for both systems. Total N uptake at physiological maturity under aerobic system at the 180 kg N ha^{-1} rate was 72 kg ha^{-1} during 2009 and 99 kg ha^{-1} during 2010. This was 40% lower than the flooded rice (121 kg ha^{-1}) during

2009 and was 20% less during 2010 (123 kg ha^{-1}) indicating higher responses to applied N in flooded rice. Significantly higher N uptake differences were observed between flooded rice and aerobic rice at 60 DAS.

Ammoniacal and Nitrate N Concentrations in Leachates

Soil solution samples were collected at 45 cm depth from the lysimeters and were analyzed for ammoniacal and nitrate-N. Results are presented in Figures 3-6 and 3- 7. In 2009, three leachate samples were collected in aerobic rice plots. Ammoniacal- N content in soil solution in the aerobic plots ranged from 0.06 to 0.35 mg L^{-1} with a mean value of 0.21 mg L^{-1} during 2009 and 0.01 to 0.46 mg L^{-1} in 2010 with a mean value of 0.13 mg L^{-1}, while in the flooded plots it ranged from 0.09 to 0.85 mg L^{-1} with a mean value of 0.29 mg L^{-1} in 2009 and 0.03 to 0.87 mg L^{-1} with a mean value of 0.19 mg L^{-1}in 2010. Significantly higher ammoniacal- N content was observed in flooded plots irrespective of the N application rate.

Nitrate-N concentration in soil solution in 2009 ranged from 0.35 to 4.2 mg L^{-1} in aerobic plots with the mean value of 1.8 mg L^{-1} and 0.33 to 3.3 mg L^{-1} with a mean value of 1.32 mg L^{-1} in 2010, while in the flooded plots it ranged from 0.45 to 4.0 mg L^{-1} with the mean value of 1.52 mg L^{-1} during 2009 and 0.34 to 2.25 mg L^{-1} with a mean value of 1.1 mg L^{-1} in 2010. Nitrate-N content increased with increased rate of N fertilizer applications over control in both the systems.

Maize Crop

Dry matter production of no-tillage maize following rice crop was neither affected by the previous crop establishment methods nor by N application to the rice crop. Yield components such as number of grains per cob and cob weight were lowest in maize grown after flooded rice (Table 3-4). Maize grown after aerobic rice however, yielded significantly higher in both years (Table 3-5). The yield increase in maize grown after aerobic rice was 5.8% and 5.3% during 2009-10 and 2010-11, respectively.

Incremental application of N rates to preceding rice crop influenced cob weight and N uptake significantly, but not the maize yields. Nitrogen uptake in maize was significantly influenced by rice establishment methods and N rates applied to rice. Nitrogen uptake was highest in maize grown after aerobic rice. Increased N uptake was noticed in maize grown after rice treatment plots receiving 180 kg N ha^{-1} than treatments receiving no N application.

Discussion

In our field study, aerobic rice method was compared with flooded rice for growth, yield and water savings. The yields of aerobic rice under present study varied from 1.9 to 5.2 t ha^{-1} compared to 3.1 to 6.4 t ha^{-1} in flooded rice. The yield difference between aerobic and flooded rice ranged from 37 to 41% during 2009 depending on the rate of N fertilizer application. In 2010, the differences between the yields in both plots were narrowed down to 16-19%. Such narrowing of yields between the two rice systems was possibly better demonstrated by the well distributed rainfall in 2010, along with improved weed management with chemical herbicides and spraying of iron sulfate for alleviating iron deficiency in aerobic plots. This suggested that effects of improved cultural and nutrient management practices will be pronounced when combined with a well-distributed rainfall during the crop season and will result in enhanced yields of aerobic systems. . However, conversion of anaerobic rice system (flooded rice) to aerobic system to save water will generally result in the rice yield reduction (Belder et al., 2005; Xiaoguang et al., 2005; Peng et al., 2006; Choudhury et al., 2007). The yield difference between aerobic and flooded rice can be attributed to reduced leaf area and biomass which may have resulted in reduced yields under aerobic rice. The yield attributing characters such as number of spikelets per panicle (sink size) and 1000- grain weight has contributed more to the yield gap between the two systems. Although the number of tillers and panicles per square meter were more under aerobic rice system, panicle length and the lesser number of filled spikelets per panicle resulted in lower grain yields. Increase in number of tillers and panicles under aerobic rice was mainly due to higher final plant population per square meter as aerobic rice was planted at 300 seeds m^{-2} rather than increase in per hill tiller and panicle number.

The total water input (irrigation + rainfall) to aerobic rice in both years ranged from 645 to 967 mm compared to 1180 to 1546 mm in flooded rice. This resulted in savings of 37-45%of water. Similar water savings and increased water productivity under aerobic rice were also reported by Belder et al. (2005) and Kato et al. (2009). The reduction in water use under aerobic rice was mainly due to water savings during land preparation as it used about 190 to 457 mm of water for land preparation in flooded rice. Under aerobic system, reduced daily drainage and evaporation losses were observed. This was mainly due to maintenance of aerobic plots at field capacity during entire crop growth period. Average aerobic rice cultivation resulted in 100% water savings in land preparation, 22.5 % savings in field water application and 47.8% savings in percolation losses. However, the yield differences between aerobic and flooded systems may outweigh the benefits of water savings. Yield losses should be limited to a maximum of 15-20% when compared to the yields attained under traditional flooded method to make aerobic rice more adoptable by the farming community. Few studies conducted in Japan reported 7.9 to 9.4 t ha^{-1} of yields under aerobic systems (Kato et al., 2009) with high yielding varieties. This demonstrates the potential for achieving similar or even higher yield levels than that achieved under traditional flooded methods through high yielding aerobic rice varieties and optimum cultural management.

The response of aerobic rice to N rates was observed up to 120 kg N ha^{-1}. Similarly flooded rice also responded to incremental doses of N up to 120 kg ha^{-1}, but the relative growth and yield levels were higher under flooded conditions. Yield response to applied N was consistent with the observed higher LAI values, aboveground biomass and increased N uptake. Lampayan et al. (2010) also noticed responses to fertilizer N up to 150 kg ha^{-1} in aerobic rice in a field study conducted on a xxx soil in Philippines. The lower N uptake in aerobic rice may have been due to increased gaseous N losses under aerobic system coupled with poor synchrony between crop needs and N availability. Further, the lower N content in grains under aerobic rice as a result of lower N uptake rates may further reduce the protein content and impact the nutritional quality of diet as rice provides 21% of global human per capita energy and 15% of per capita protein (Maclean et al., 2002). In the present experiment higher concentrations of nitrates in aerobic rice and ammoniacal N in flooded rice was observed in leachates collected below root zone in rice. The higher concentrations of nitrates compared to ammoniacal N in aerobic rice potentially pose a higher risk leaching. Even though the nitrate concentrations in our study are below the EPA drinking water limits, under light texture soils, increased N rates may result in increased risk of nitrate leaching into the ground water, as it still is a predominant source of drinking water.

Research work on aerobic rice in the Indian subcontinent is limited. For aerobic system (dry planted & irrigated conditions), availability of genetic pools is also limited. However, for rainfed upland situations, few varieties were developed even though the yields still are relatively low. Lack of high yielding varieties that can provide higher yields under aerobic conditions is a major challenge for aerobic rice cultivation in India. Among the varieties recommended for low land transplanted conditions, medium and short duration varieties, which mature in less than 120 days, are recommended for aerobic conditions. In this study, a high yielding popular low land variety MTU-1010 was used. An exclusive breeding program for aerobic varieties initiated in Japan (Nemoto et al., 1998) and China (Wang et al., 2002) resulted in promising yields for their respective regions. Similar initiative is needed for Indian sub-continent, where exclusive aerobic rice varieties can be developed.

In the traditional flooded rice method of establishment, the field is flooded and puddled. The puddling operation destroys soil structure impacting the subsequent crop establishment and growth. Further, the too wet conditions after rice crop harvest delays land preparation and timely planting of following crop causing a yield decline. Adopting aerobic rice cultivation may result in early maturity and better residual soil physical conditions congenial for succeeding crops. Results in our study showed increased maize yields followed by aerobic rice for both years (Table 3-5). Similar increased yields for succeeding crops followed by rice grown under un-puddled conditions were reported by Hobbs et al. (2000); Singh et al. (2002); Sharma et al. (2005) ; Singh et al. (2008).

Aerobic rice can be a viable option for growing rice for water deficit regions and by proper management up to 80% yields attainable under flooded system can be obtained.

Timely planting, proper establishment, water management, and higher yields of succeeding maize crop can be achieved with maize followed by aerobic rice.

Table 3-1. Components of the seasonal water balance (mm) of rice and maize during 2009-10 and 2010-11 under flooded and aerobic conditions.

Treatment	Rice					Maize				
	I (mm)	ER (mm)	ΔW (mm)	ET (mm)	DP (mm)	I (mm)	ER (mm)	ΔW (mm)	ET (mm)	DP (mm)
2009-10										
Aerobic	625	342	86	438	443	390	0	46	329	15
Flooded	757*	332	0	409	680	380	0	28	342	10
2010-11										
Aerobic	0	645	17	369	259	340	19	25	324	10
Flooded	550*	441	0	355	636	300	19	-16	335	0

Irrigation amounts shown are the total volumes from planting to harvest in aerobic rice and from transplanting to harvest in flooded rice.

I= irrigation ; ER effective rainfall; ET , Evapotranspiration; DP, deep percolation; ΔW, Change in stored soil water content.

*I for flooded rice do not include the water applied during puddling (457 mm in 2009 and 191 mm in 2010).

Table 3-2. Water supply (irrigation plus effective rainfall) and water productivity (WP) (g grain kg^{-1} water) of rice and maize during 2009-10 and 2010-11 under flooded and aerobic conditions.

Treatment	Rice				Maize				Rice-Maize System			
	Water supply		WP_{IR}		Water supply		WP_{IR}		Water supply		WP_{IR}	
	2009	2010	2009	2010	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11
Aerobic	967	645	0.31	0.62	390	359	1.52	1.81	1357	1004	0.66	1.05
Flooded	1546	1180	0.32	0.40	380	319	1.47	1.94	1926	1499	0.54	0.73
ANOVA												
Method (M)			**	***			*	***			***	***
N rates (N)			***	***			NS	NS			***	***
M X N			NS	NS			NS	NS			NS	NS

Water supply in flooded plots includes irrigations for puddling* P< 0.05, ** P<0.01, *** P<0.001. NS= non-significant (p>0.05).

Table 3-3. Yield components of rice during 2009 and 2010 under flooded and aerobic conditions.

Treatment	Number of panicles m^{-2}		Spikelet number $panicle^{-1}$		1000 grain weight (g)	
	2009	2010	2009	2010	2009	2010
Aerobic- 0 N	291	210	53	68	17.2	18.1
Aerobic- 60 N	314	287	72	75	18.2	19.0
Aerobic- 120 N	343	328	82	103	18.7	19.5
Aerobic- 180 N	388	367	103	125	19.2	20.4
Flooded-0 N	230	184	100	97	20.8	20.7
Flooded-60 N	255	238	122	116	21.6	21.7
Flooded-120 N	306	308	132	128	22.1	22.2
Flooded-180 N	341	336	149	142	22.4	22.5
ANOVA						
Method (M)	***	**	***	***	***	***
N rates (N)	***	***	***	***	***	***
M X N	NS	NS	NS	*	NS	***

* P< 0.05, ** P<0.01, *** P<0.001. NS= non-significant (p>0.05).

Table 3-4. Yield components of maize during 2009-10 and 2010-10 as influenced by rice crop establishment methods and N rates.

Treatment	Cob weight (g)		100 grain weight (g)		Grain number cob^{-1}	
	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11
AR-0 N-M-120	131	141	27.7	28.1	418	433
AR-60 N-M-120	135	142	27.2	28.6	428	448
AR-120 N-M-120	137	147	27.7	28.9	428	462
AR-180 N-M-120	141	150	28.1	29.0	435	477
FR-0 N-M-120	125	131	26.9	28.0	396	409
FR-60 N-M-120	131	137	27.0	27.8	408	430
FR-120 N-M-120	132	138	27.6	27.8	419	445
FR-180 N-M-120	129	141	27.3	27.9	426	442
ANOVA						
Method (M)	***	***	*	**	*	**
N rates (N)	*	*	NS	NS	NS	**
M X N	NS	NS	NS	NS	NS	NS

* P< 0.05, ** P<0.01, *** P<0.001. NS= non-significant (p>0.05). AR= Aerobic rice, FR = Flooded rice, M= Maize.

Table 3-5. Yield (t ha^{-1}) and N uptake (kg ha^{-1}) of maize during 2009-10 and 2010-10 as influenced by rice crop establishment methods and N rates.

Treatment	Grain Yield		N uptake	
	2009-10	2010-11	2009-10	2010-11
AR-0 N-M-120	5.74	6.30	127	142
AR-60 N-M-120	5.90	6.47	135	151
AR-120 N-M-120	5.88	6.51	140	155
AR-180 N-M-120	6.15	6.73	147	162
FR-0 N-M-120	5.42	5.96	119	133
FR-60 N-M-120	5.47	6.02	122	136
FR-120 N-M-120	5.72	6.31	130	146
FR-180 N-M-120	5.77	6.42	133	150
ANOVA				
Method (M)	*	*	**	**
N rates (N)	NS	NS	**	**
M X N	NS	NS	NS	NS

* P< 0.05, ** P<0.01, *** P<0.001. NS= non-significant (p>0.05). AR= Aerobic rice, FR = Flooded rice, M= Maize.

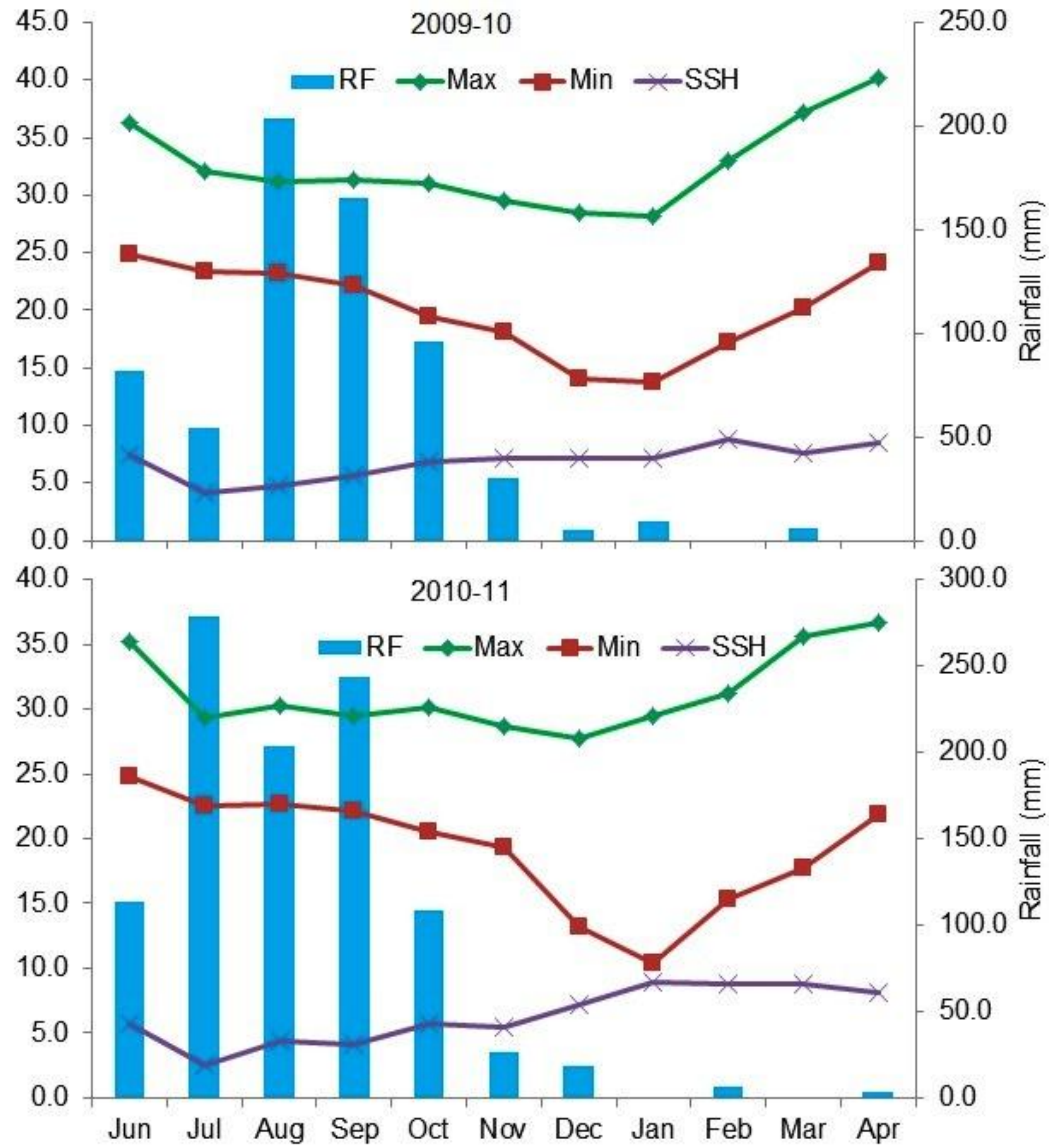
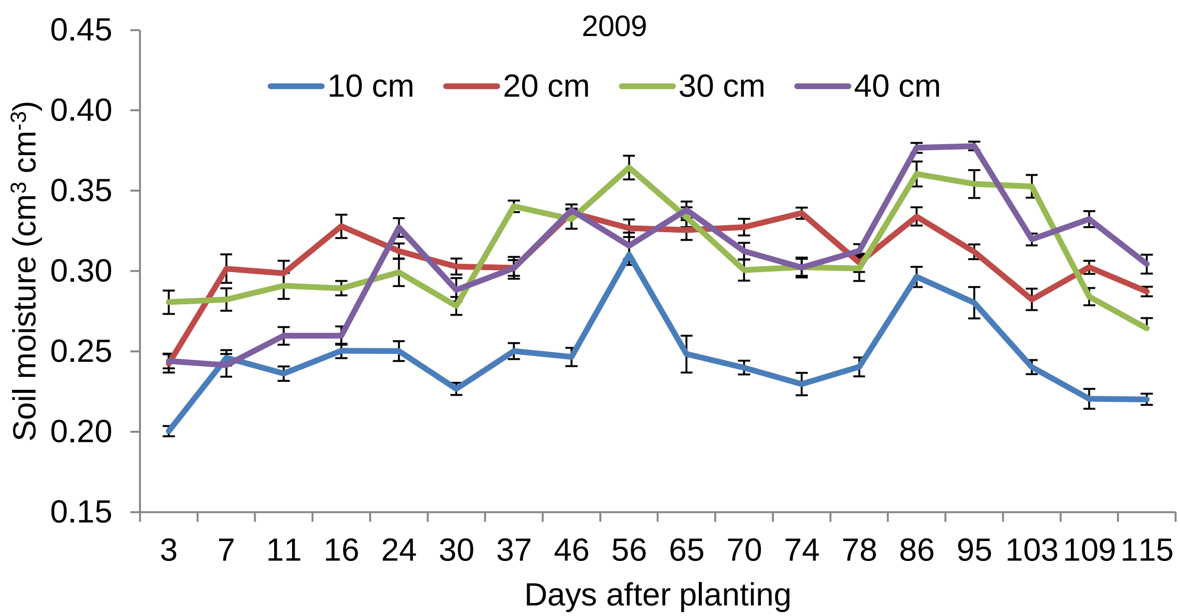


Figure 3-1. Monthly rainfall (RF, mm), mean maximum temeprature (^oC), mean minimum temeprature (^oC) and mean number of bright sunshine hours (SSH) in Hyderabad during 2009-10 and 2010-11.



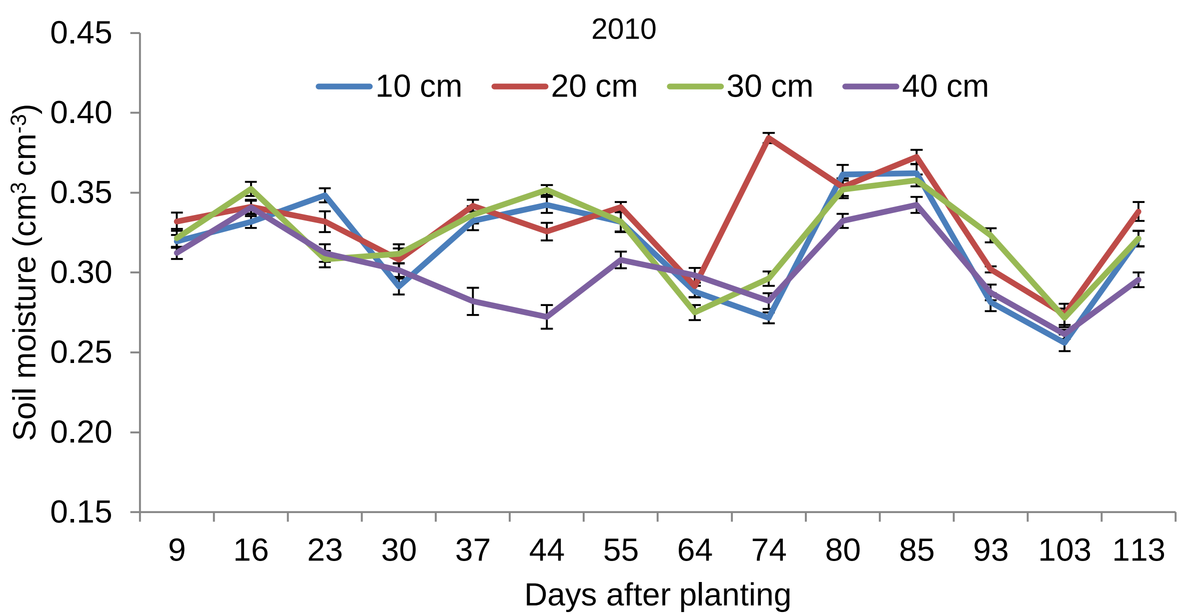


Figure 3-2. Volumetric soil moisture content recorded in aerobic plots at 10, 20, 20 and 40 cm soil depth during the 2009 and 2010 growing seasons. Bars indicate the standard error.

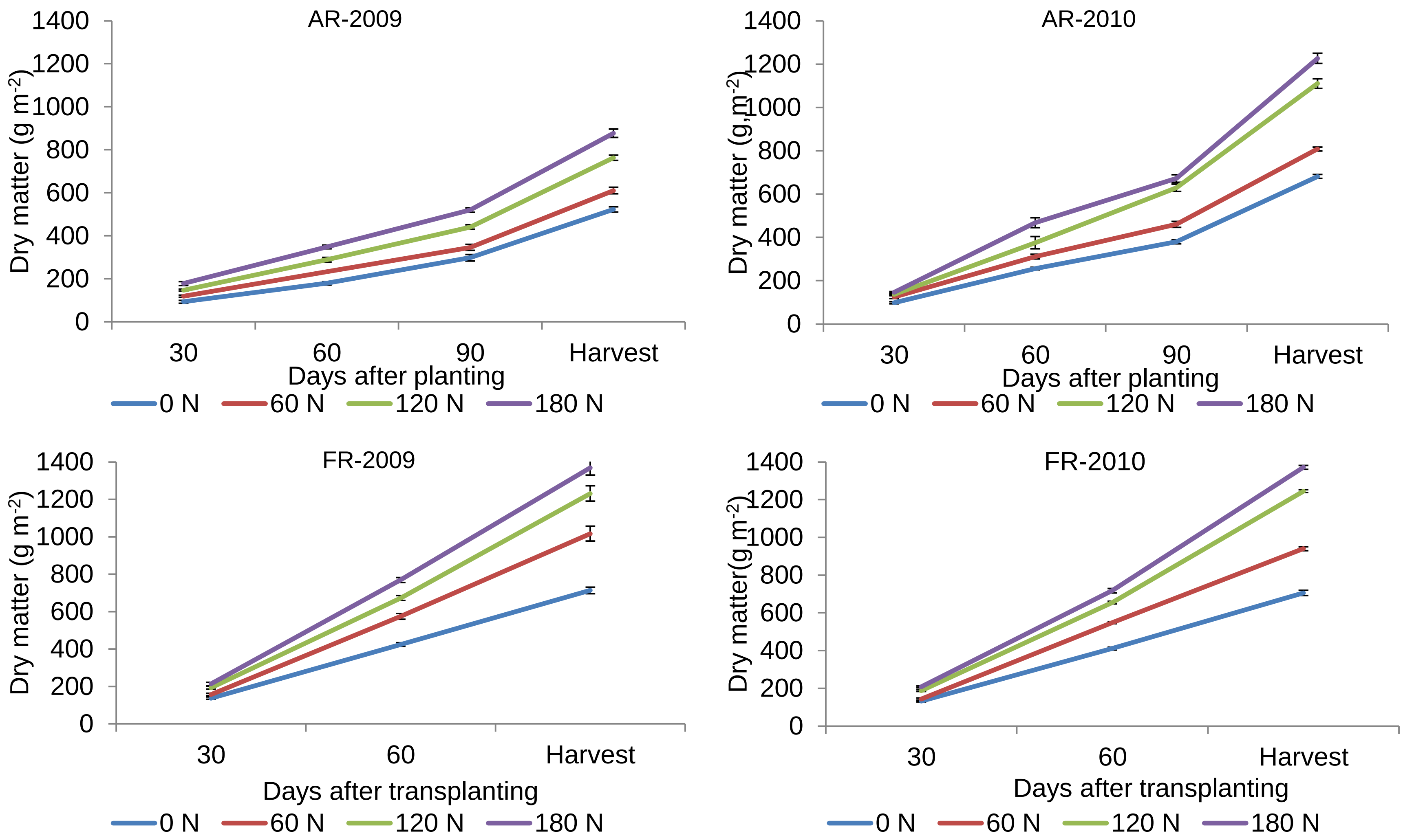


Figure 3-3. Drymatter production of rice under aerobic (AR) and flooded (FR) condtions at different N fertilizer rates during 2009 and 2010. Bars indicate the standard error.

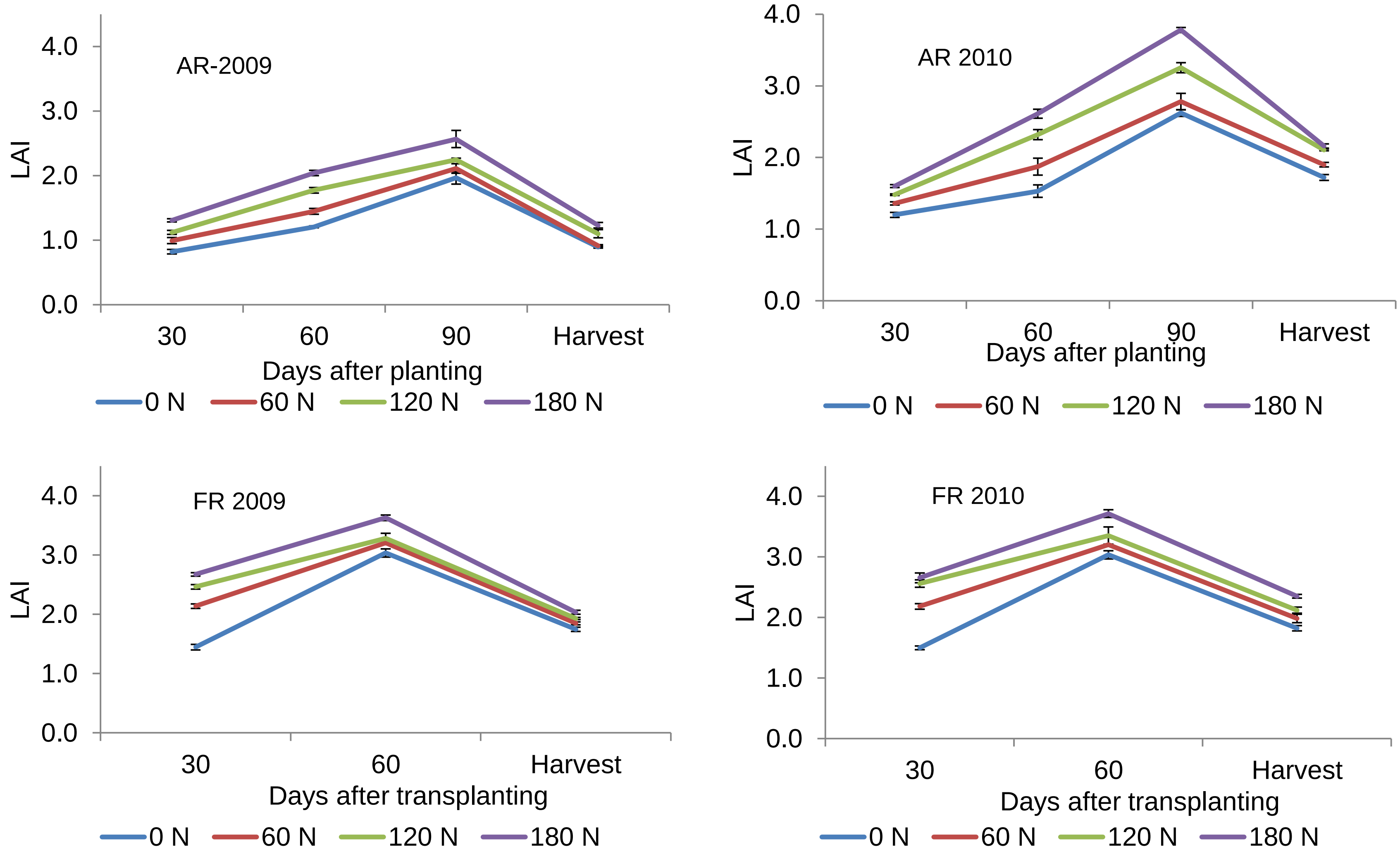


Figure 3-4. Leaf area index (LAI) of rice under aerobic (AR) and flooded (FR) conditions at different N fertilizer rates during 2009 and 2010. Bars indicate the standard error.

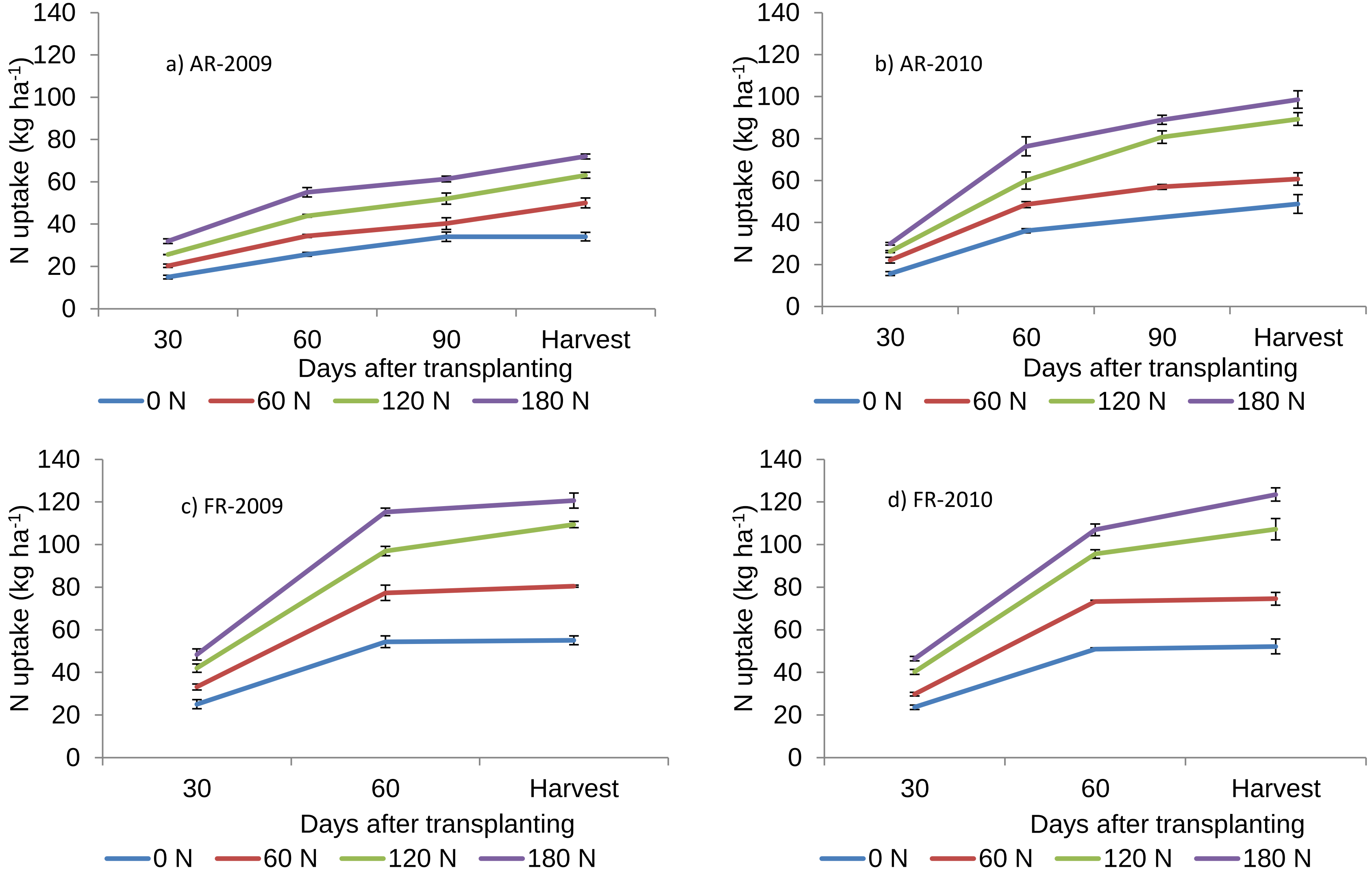


Figure 3-5. Nitrogen uptake in rice under aerobic (AR) and flooded (FR) conditions at different N fertilizer rates during 2009 and 2010. Bars indicate the standard error.

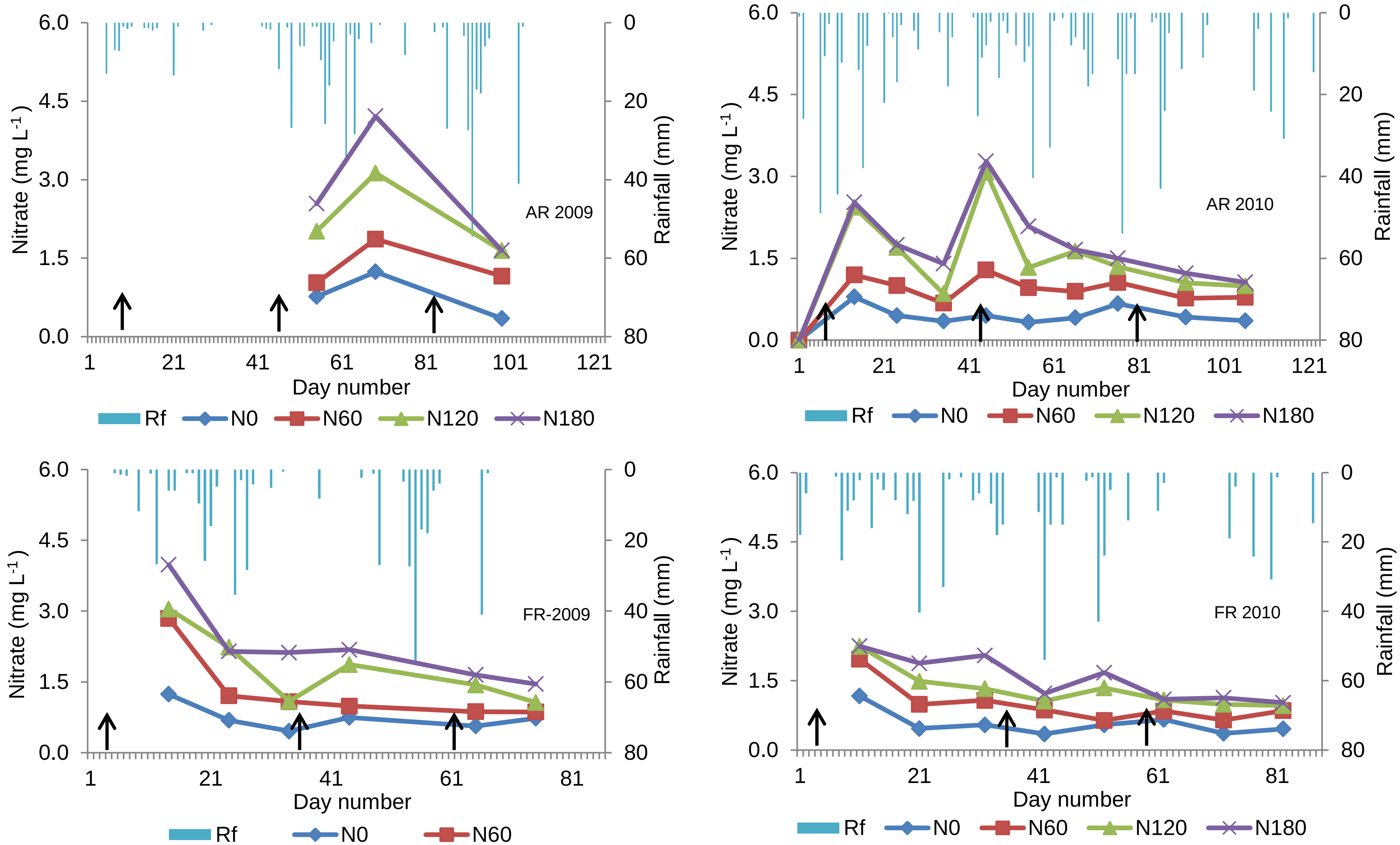


Figure 3-6. Nitrate concentrations in ground water in aerobic and flooded plots during 2009. Arrows indicate the dates of N fertilizer application.

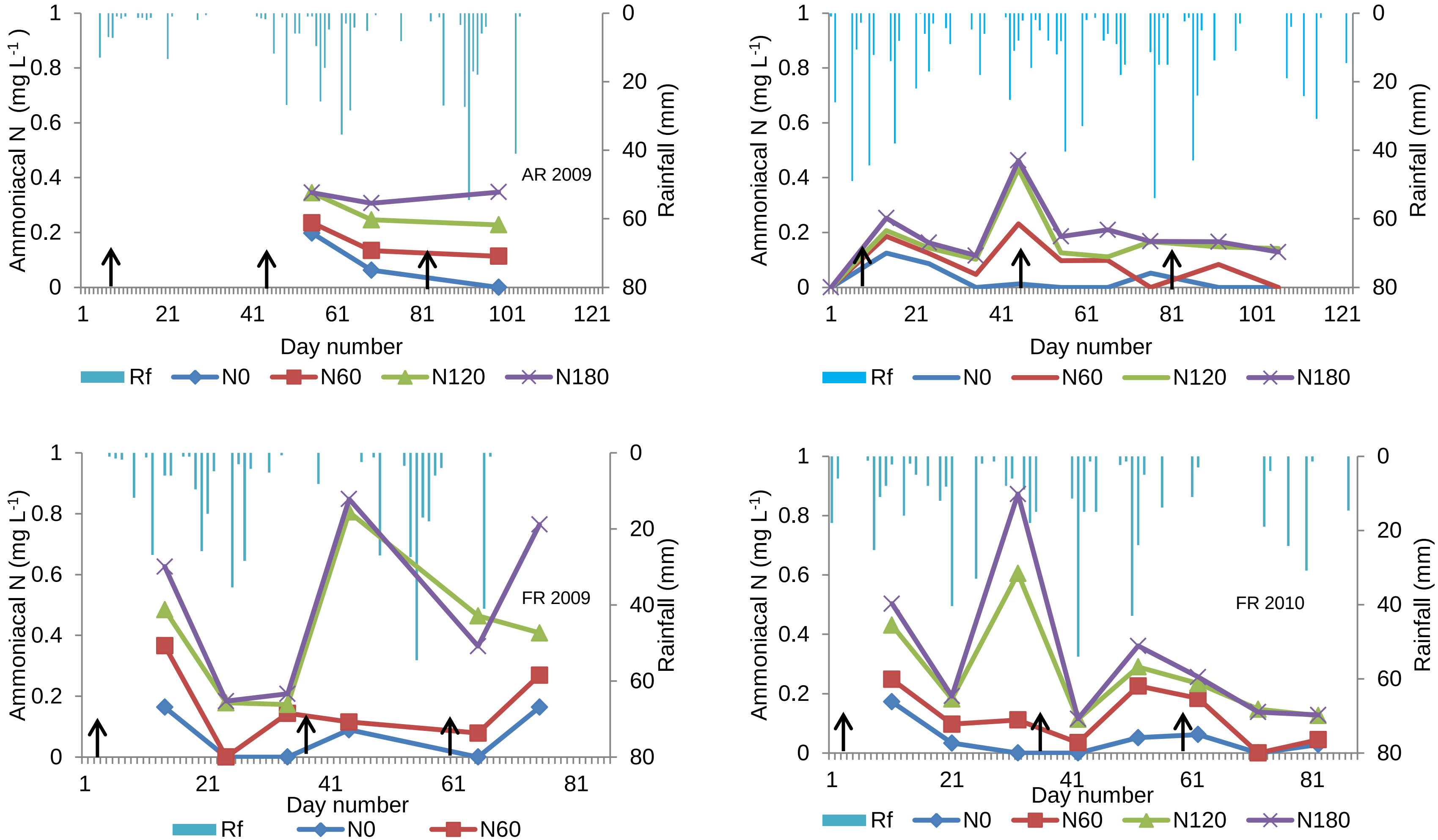


Figure 3-7. Ammoniacal N concentrations in ground water in aerobic and flooded plots during 2009. Arrows indicate the dates of N fertilizer application.

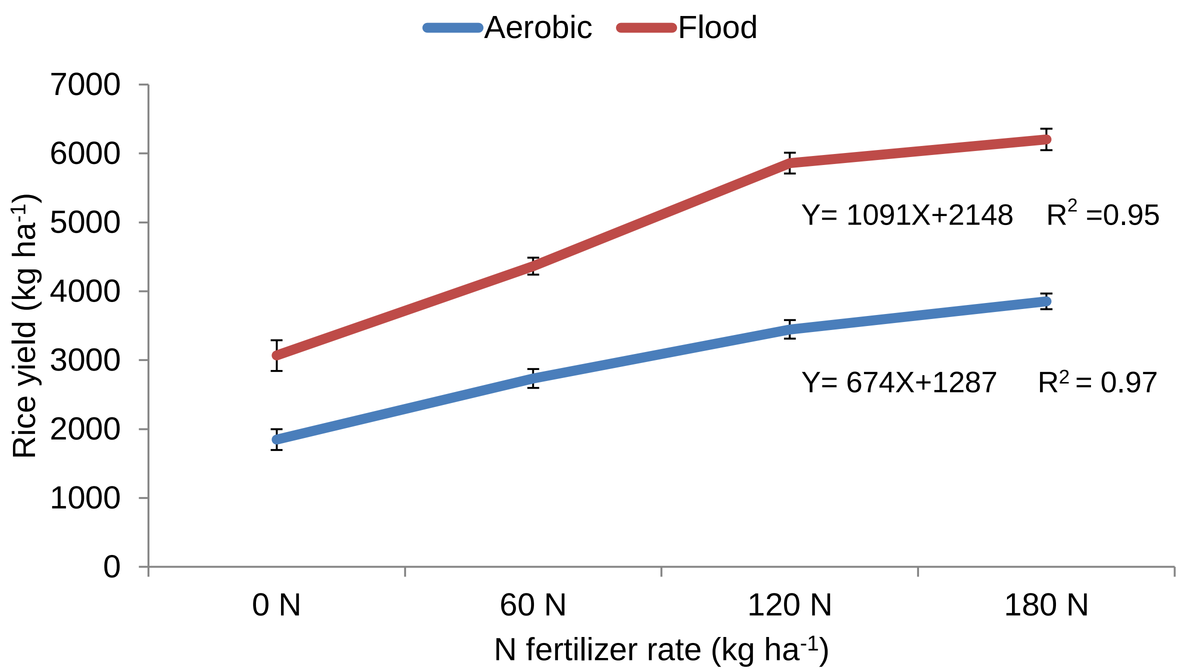


Figure 3-8. Grain yields (kg ha^{-1}) rice as influenced by rice establishment methods and N rates during 2009. Bars indicate the standard error.

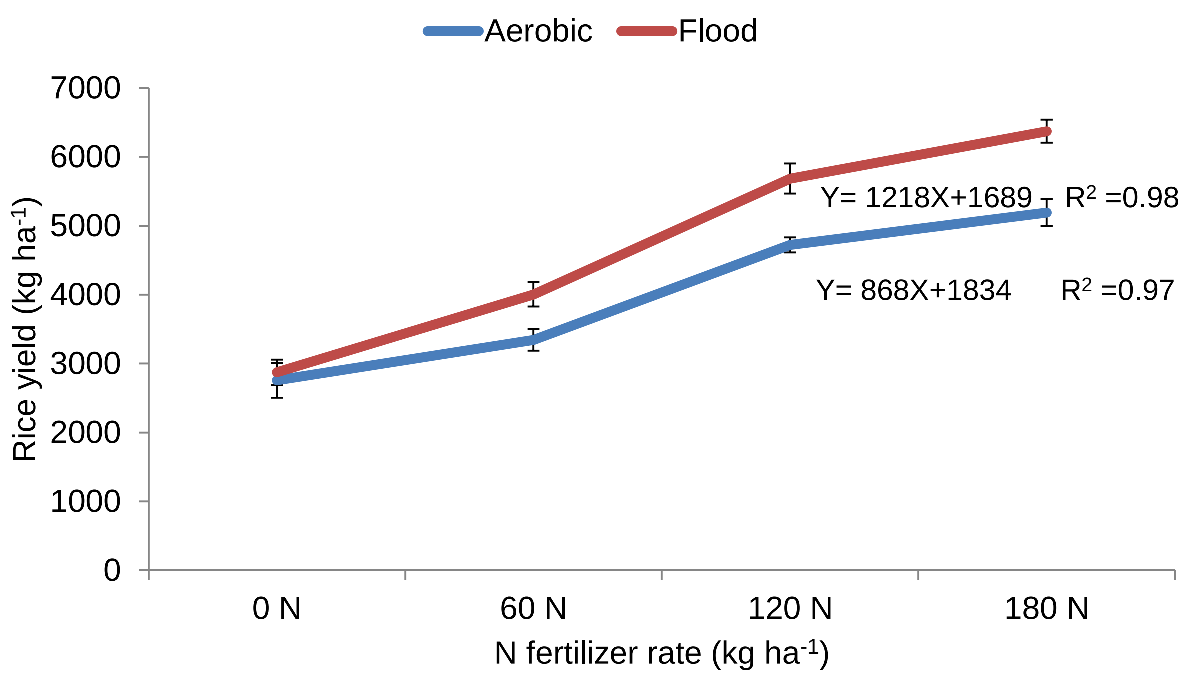


Figure 3-9. Grain yields (kg ha^{-1}) rice as influenced by rice establishment methods and N rates during 2010. Bars indicate the standard error.

CHAPTER 4
FATE OF FERTILIZER ^{15}N IN RICE AS INFLUENCED BY METHOD OF ESTABLISHMENT AND NITROGEN RATES UNDER SEMI-ARID CONDITIONS

Background

Nitrogen (N) is a very critical nutrient required for rice crop growth and yield (Yoshida, 1981) and efficient use of N fertilizer is very important to maximize the returns and to minimize environmental impacts. Nitrogen fertilizer use efficiency (NUE) is very low in irrigated rice systems and most of the applied fertilizer N is rapidly lost from a rice field mainly through volatilization and denitrification (De Datta and Buresh, 1989). De Datta et al. (1991) reported that of the total urea applied, up to 50% can be lost through ammonia volatilization while up to 10% can be lost through denitrification, in the tropical rice ecosystems. In spite of adopting optimized timing, rate, placement and sources of inorganic N, the NUE of rice is still in the range of 30-40% (Prasad and De Datta, 1979; De Datta and Creswell, 1982; Fillery and Vlek, 1986; Cassman et al., 1993). Extensive losses coupled with traditional fertilizer application practices made N management as one of the primary factors affecting rice production in any rice establishment method (Mikkelsen, 1987). Since N is the most difficult of plant nutrients to manage, knowledge on N transformation pathways is vital to determining management practices for efficient N use (De Datta and Patrick, 1986; Mikkelsen, 1987).

Rice production in the world is threatened by severe water shortage and several technologies have been tried to reduce water loss and improve the water productivity. Aerobic rice is one such option, which is a new way of growing rice in water shortage areas where fields are always maintained at near saturation instead of flooding through the cropping season. The induced changes in water regime in aerobic system will result in altered soil N transformations and plant N uptake patterns. In aerobic rice system, the dominant form of N was found to be nitrate, with obvious reduction in ammonia volatilization (Belder et al., 2005; Zhang et al., 2009). Few studies in rice indicated that a mixture of nitrate and ammoniacal forms of N is better for uptake and growth of rice plants than any one form (Ta et al., 1981; Qian et al., 2004). Therefore, rice production employing water saving techniques may result in higher N uptake but also may result in higher N loss and reduced growth if nitrate availability and plant growth do not coincide. Nitrogen transformations in lowland soils have been studied extensively (De Datta, 1968; Reddy and Patrick, 1976, De Datta and Buresh, 1989; Buresh and De Datta, 1991; George et al., 1992; Kundu and Ladha, 1995). Current N fertilizer recommendations for rice in general have, therefore, been established for rice production under continuously submerged conditions. Since the aerobic rice concept is recent, relatively fewer studies were conducted on N dynamics and N fertilizer efficiencies. Results from a field study in southern India reported that under aerobic conditions the response of rice to applied N was up to 175 kg N ha^{-1} (Sathiya et al., 2008). However, generating information on N dynamics and NUE for other regions of the world may be critical as aerobic method of rice production is being increasingly adopted as a significant technique to achieve water conservation.

As conservation of limited water resources has become critical, the traditional rice-rice productions systems have shifted to rice-maize (R-M) systems. Further, the rice establishment method itself is shifting from flooded to aerobic system. The R-M system is gaining popularity in many Asian countries due to rapidly increasing livestock and human populations. Nitrogen dynamics and balances in R-M cropping system have not been explored. Additional research is required to understand the various nutritional aspects of R-M systems that would improve productivity, profitability, and sustainability. The ^{15}N labeled fertilizers can effectively be utilized to study the flow and fate of N between crops in crop sequence studies, as it allows accurate quantification of applied N in various sinks such as crops, available soil N and soil organic matter N pools (Shinde et al., 1985; Timmons and Cruse, 1991; Powlson and Barraclough, 1993; Singh et al., 2001). Information on long-term N retention patterns in nutrient intensive R-M cropping systems, especially under changed rice establishment methods, is essential to evaluate the effect on NUE of the entire cropping system. A field experiment was conducted with ^{15}N labeled fertilizer in aerobic and flooded R-M cropping system to (i) study the effect of N rates on yield and N uptake of aerobic rice in comparison with flooded rice, (ii) determine the total recovery of applied inorganic N in the crop and soil in R-M rotation, and (iii) study the residual effect of inorganic N on ^{15}N uptake by subsequent crops.

Materials and Methods

A field experiment was conducted over two consecutive years (2009-10 and 2010-11) in a rice-maize cropping sequence at the Acharya NG Ranga Agricultural University Research farm, Hyderabad, India. The soil at the experimental site was a sandy loam soil with a pH of 8.0, organic C of 0.51%, $KMnO_4$ extractable N of 202 kg ha^{-1} , Olsen's extractable P of 24.7kg ha^{-1} and ammonium acetate extractable K of 250 kg ha^{-1} in the surface 15 cm soil (Table 4-1). The experiment was laid out in a split plot design with rice crop establishment methods as the main plots and N levels as sub plots with three replications. The two rice establishment techniques were (i) Aerobic rice - the land was dry ploughed, harrowed , leveled, and dry seeded manually with MTU-1010 variety spacing at 22.5 cm in a row with a seed rate of 300 seeds m^{-2} and (ii) Flooded rice - the flooded plots were puddled and were kept under flooded conditions from transplanting until one week before harvest. Rice seedlings (30 days old) were transplanted at a spacing of 20 x 15 cm. The nursery plantings for flooded plots were done on the same day of the planting of aerobic plots. Four N treatments were selected for the study- (i) No N (0 kg ha^{-1}), (ii) 60 kg ha^{-1}, (iii) 120 kg ha^{-1}, and (iv) 180 kg ha^{-1}.

Microplots within each main plot were created by inserting leak- proof, galvanized iron frames (2.0 m long, × 2.0 m wide x 0.6 m high) with top and bottom open were inserted to a 30 cm depth in aerobic and flooded treatment plots. The main purpose of using these micro plots was to control lateral movement of water, to facilitate measurement of vertical flow and to confine ^{15}N fertilizer within the microplot. The fertilizer N was applied in the form of urea in three equal splits- the first one as basal and the other two, at active tillering and at panicle initiation stages. The required quantity of urea according to the treatments was applied to the entire plot uniformly except the microplots. The microplots were covered with polythene sheets at the time of urea application on main plots so that the fertilizer urea may not spill into the microplots. The microplots were fertilized with ^{15}N labeled urea having 5 atom% excess ^{15}N according to the treatments in three splits. All the urea applied in plots was incorporated into the soil. The whole plot including microplot received a uniform rate of 26 kg ha^{-1} P as single superphosphate and 33 kg ha^{-1} K as muriate of potash (KCl) at the time of planting in aerobic method and at final puddling in flooded treatment. All the required plant protection measures were adopted during the crop growth as per the standard procedures.

At physiological maturity, yield components such as number of panicles m^{-2}, number of spikelets per panicle, 1000 grain weight were determined. Grain and straw samples from net plot area of 49 m^2 in the main plots and entire microplot were collected and dried at 60^0 C until a constant weight was attained. Aerobic rice plots were harvested during 1st week of November and flooded rice plots a week later (2nd week of November) due to delay in maturity. Grain and straw samples at harvest were also measured for N content and total N uptake was computed (Jackson, 1973). Grain, straw and weeds grown in all micro plots were ground in a ball mill to pass through 1 mm sieve and were analyzed for atom excess percent using mass spectrophotometer (Delta V plus, Thermo Fisher Scientific, Bremen, Germany). Soil samples were collected in all microplots from several spots at 15 and 30 cm depth, air dried, ground to pass 2 mm sieve, and were analyzed for ^{15}N. Total-N and atom% ^{15}N were analyzed using an Isotope ratio mass spectrometer at University of Agricultural Sciences, Bengaluru, India.

After the harvest of rice crop the plots were kept fallow for 15 days and maize (DeKalb 800 m variety) was grown in the succeeding season under no tillage conditions in both main and micro plots. A uniform application rate of 120 kg N ha^{-1}, 26 kg P ha^{-1} and 33 kg ha^{-1} K were applied for entire plot including microplot. Plant biomass, yield components and final yield were recorded. Maize crop was harvested in the last week of March during both the years. The grain and straw samples of maize in microplots were prepared and analyzed as same as rice samples described previously. Soil samples were collected in all microplots at 15 and 30 cm depth to analyze for ^{15}N to study residual soil N, if any. The microplots were left in place throughout the study. During the second year, a new set of microplots with galvanized iron sheets, measuring (1.0 m × 1.0 m x 2.0 m) were established to repeat the study. Micro plots established during the first year were used to study the residual effect of N applied in the preceding year.

Apparent N recovery (APR %) and N Use Efficiency (NUE) were calculated with the difference method using the total plant N uptake at physiological maturity.

$$\text{APR (\%)} = \frac{N_f - N_{uf}}{N_a} \times 100 \tag{4-1}$$

where N_f and N_{uf} were total N uptake in fertilized and unfertilized plots (kg ha^{-1}) respectively, and N_a is the total amount of fertilizer N applied (kg ha^{-1}).

$$\text{NUE (kg grain kg N applied}^{-1}\text{)} = \frac{GY_f - GY_{uf}}{N_a} \tag{4-2}$$

where GY_f and GY_{uf} were the grain yield in fertilized and unfertilized plots (kg ha^{-1}) respectively, and N_a is the total amount of fertilizer N applied (kg ha^{-1}).

Percentage recovery of ^{15}N in plant or soil was calculated using the formula of Hauck and Bremner (1976).

$$\text{Percentage N recovered} = \frac{100\ TN\ (A_f - A_{uf})}{F(A_u - A_{uf})} \tag{4-3}$$

where TN is the total N in the plant part or soil (kg ha^{-1}); F is the rate of ^{15}N fertilizer applied (depending upon the treatment from 60 to 180 kg ha^{-1}); and Au, Auf, and Af are the atom% ^{15}N in the labeled urea fertilizer (5%), plant part or soil receiving no ^{15}N (equals to natural abundance), and plant or soil receiving ^{15}N, respectively. Soil N contributed through mineralization was calculated by subtracting N recovery from labeled urea from total N accumulation in plant.

Leaching

Suction lysimeters were installed vertically to a depth of 45 cm to collect soil pore water samples in each microplot as described in Chapter 3. The rate of water percolated out of root zone in flooded treatments was measured using lysimeters throughout the crop growth period as described by Bethune et al., 2001. In aerobic plots, deep percolation beyond root zone was estimated using the water balance method (Wilis et al., 1997). Nitrogen leaching loss was computed by multiplying nitrate and ammoniacal concentrations in the soil solution below the root zone with the total volume of water percolating out of the root zone per hectare. Percentage of fertilizer N lost through leaching was estimated by measuring ^{15}N in the leachate samples.

Statistical Analysis

All the data on yield and yield attributes of rice and maize, N uptake were analyzed with IRRISTAT for windows consisted of analysis of variance (ANOVA), with rice establishment method and N levels as main and sub treatments, respectively (Bartolome et al., 1999). Wherever the treatments were found significant, pair wise testing with t test was performed among the main and subplot treatments. The level of confidence was set at 95%.

Results

Nitrogen Uptake

Average total uptake of N at physiological maturity under different treatments ranged from 50.0 kg ha^{-1} in 60 kg N rate to 85.3 kg ha^{-1} at 180 kg N rate in aerobic rice treatments while it was 80.5 kg ha^{-1} with 60 kg N to 120.6 kg ha^{-1} at 180 kg N in flooded treatments (Table 4-2). The total N uptake was higher by 61.0%, 71.0%, and 67.5 % in flooded rice compared to aerobic rice with 60, 120 and 180 kg N application, respectively in the year 2009, while the increase was 22.9%, 20.0% and 25.3% during 2010 (Table 3), indicating the enhanced response to increased N applications in flooded rice.

Nitrogen Recovery Efficiency

Method of establishment has a profound effect on N recovery (APR) and N use efficiency (NUE) in rice. The APR of applied urea fertilizer ranged from 21.1 to 26.6 % in 2009 and 19.8 to 33.7% in 2010 under aerobic rice system (Figure 4-1). The APR in flooded plots, however, ranged from 36.4 to 45.3% in 2009 and 37.3% to 45.8% in 2010 with the difference method. The average NUE, i.e. kilogram of grain produced per kilogram of N applied, was in both years significantly lower in aerobic plots (13.2 kg kg^{-1}) compared to flooded plots (20.7 kg kg^{-1}).

The recovery of fertilizer N applied to rice was studied using ^{15}N method in grains, straw, weeds of rice and the subsequent maize crop. In the rice season, during both the years, the fertilizer N recovery in grain and straw was higher in flooded rice (18.7 to 58.7 kg ha^{-1} and 17.5 to 56.1 kg ha^{-1}in 2009 and 2010, respectively) compared to aerobic rice (8.8 kg ha^{-1} to 30.1 kg ha^{-1} and 14.5 kg ha^{-1} to 45.7 kg ha^{-1} in 2009 and 2010, respectively) (Table 4-2). During the second year of rice crop, an additional recovery in the order of 0.42 to 2.10 kg ha^{-1} in aerobic rice plots and 0.75 to 1.84 kg ha^{-1} in flooded rice was recovered from the 1st year application (Table 4-3). The recovery of fertilizer N increased with increased dose of N up to 180 kg N ha^{-1}; however, the percent recovery decreased in both the systems beyond 120 kg ha^{-1}. The 2-year average of N recovery was 11.7, 27.0 and 37.9 kg ha^{-1} from plots that received 60, 120 and 180 kg in aerobic rice. The corresponding recoveries recorded were significantly higher in flooded plots (18.1, 41.6 and 57.4 kg ha^{-1}). The recovery percent was highest at the applied N rate of

120 kg N ha^{-1} from both the systems. The average N recovery efficiency with N difference method was 5-9% greater compared to the amount estimated isotopic method for both the systems in both the years.

Soil N Contribution to Rice Crop

Crop demands for N can be met from application of inorganic fertilizer or through mineralization from soil organic pool. From the experimental results, it was evident that soil mineralization of organic matter was the main source of N in rice. Unlabeled N from soil mineralization accounted for 67.4 - 62.8% of the total N in the crop in aerobic and 61.4 -62.6% in flooded rice during 2009 and 2010, respectively, which indicated that the average quantities derived from soil, were 41.8 kg in aerobic and 63.5 kg in flooded rice during 2009 and 52.0 and 63.7 kg in 2010 including the residual N received from 2009 application (Table 4-3). There were no significant differences observed in soil N contributions across N rates indicating that the rice crop obtained similar amounts of N from soil irrespective of N rates. These results confirm the importance of soil as a source of N, even in tropical soils with typical organic carbon contents around 0.50%.

Nitrogen Recovery by Weeds

The average fertilizer recovery by weeds in the both years of the study was highest in aerobic rice with recoveries ranging from 0.6 to 1.3% during 2009 and 0.62 to 0.71% during 2010, respectively (Tables 4-4 and 4-5). Aerobic rice establishment method presented a unique situation where weed proliferation was significant. In flooded situations, weeds were prevented due to continuous submerged conditions. The recoveries of ^{15}N were therefore, significantly higher in aerobic rice during both the years.

Nitrogen Recovery in Leachates

The total losses of applied fertilizer through leaching in aerobic system ranged from 1.2 to 4.3% during 2009 and 1.7 to 5.1% in 2010 compared to 1.6 to 5.0% in 2009 and 1.8 to 5.6 % in 2010 under flooded rice system (Tables 4-4 and 4-5). Of the total N leached over the two years, average fertilizer N leached was determined to be between 23–88% in aerobic rice and 24-93% in flooded rice. The contribution of applied fertilizer in inorganic N leaching increased with increased N rate applied under both the systems.

The unaccounted ^{15}N in soil plant system at the harvest of rice varied between 38.7 and 97.9 kg ha^{-1} in 2009 and 31.5 and 76.9 kg ha^{-1} in 2010 in aerobic rice; in flooded rice, it was found to be between 26.1 and 63.9 kg ha^{-1} in 2009 and 26.8 and 62.4 kg ha^{-1} in 2010.

Nitrogen Recovery in Soil between Rice Harvest and Maize Planting

After the harvest of rice crop in R-M rotation, a significant amount of fertilizer N was recovered in the surface 30 cm soil in both the systems, potentially available for subsequent crops. In the year 2009 flooded system recorded significantly higher amount of measured ^{15}N (14.2-48.2 kg ha^{-1}) compared to aerobic rice system (11.4-42 kg ha^{-1}) (Table 4-2). In the year 2010, in flooded rice plots 22.5 kg ha^{-1} to, 76.9 kg ha^{-1} of ^{15}N was recovered in the soil which includes 7.8 to 25.5 kg ha^{-1} from the ^{15}N applied in 2009, whereas, in aerobic rice in 2010, 19.8-72.4 kg ha^{-1} of fertilizer N was recovered, out of which 7.2 to 25.3 kg ha^{-1} was residual from the year 2009 (Table 4-3).

Nitrogen Recovery in Soil between Maize Harvest and Rice Planting

The soil samples after the harvest of maize were analyzed for ^{15}N. Average recoveries of 21.2 kg ha^{-1} (range from 10.5-31.4 kg ha^{-1}) in flooded R-M system and 20.0 kg ha^{-1} (ranges from 8.2 to 32.0) in aerobic R-M plots were recorded during 2009-

10 (Table 4-6). The results of the fourth season soil sampling in maize, during 2010-11 revealed that in flooded plots 18.1 to 65.1 kg ha^{-1} fertilizer N, which includes 6.7 to 23.1 kg ha^{-1} from the 1st season ^{15}N, was recovered. Similarly, maize (followed by aerobic rice), 16.6 to 62.4 kg ha^{-1} fertilizer N including 6.4 to 23.1 kg ha^{-1} from the 1st season was recovered in the soil (Table 4-7). Overall soil recovery studies indicated that significant fraction of the applied inorganic fertilizers were recovered in the soil, which will play a major role in replenishing soil organic N pools and maintain the soil fertility status.

Nitrogen Recovery in Succeeding Crops

Determination of the amount of residual N credited from the first crop to the subsequent crop is essential to determine the supplemental N needed for the subsequent crop in a cropping sequence. After the harvest of the rice crop, average recovery of N by the subsequent maize crop from applied N to the rice crop in both the systems was ranged from 2.0 to 8.0 kg ha^{-1} (3.3 to 4.5%). However, maize crop that followed aerobic rice showed the highest utilization of residual fertilizer N (1.9 to 8.2 kg ha^{-1} during 2009-10 and 2.15 to 7.88 kg ha^{-1} during 2010-11) compared to flooded rice (1.8 to 6.5 kg ha^{-1} and 2.18 to 6.6 during 2009-10 and 2010-11, respectively)(Tables 4-6 and 4-7). The fraction of fertilizer recovered in the subsequent third and fourth crop was very low. The third season recoveries from rice ranged from 0.7 to 1.53% and 0.27 to 0.38% in fourth season maize indicating that most of the fertilizer N recovery was completed by maize in the second growing season (Table 4-8 and Figure 4-2). From the residual studies it was observed that the recoveries by subsequent crops after rice in both aerobic and flooded systems were very small and will not be adequate to meet N requirements in any substantial way.

Discussion

Aerobic rice technology was developed as a potential tool for rice growing areas of Asia facing serious water shortages. Growing rice under conventional irrigation usually takes twice as much water compared to other major crops such as wheat and maize. The present studies on the response of aerobic rice to incremental rates of N in comparison with flooded rice demonstrated larger differences in yield and N recoveries, which were closely related to differences in N dynamics observed in both the systems.

Fertilizer N recovery in rice was estimated by both N difference and ^{15}N isotopic methods. Values of NUE estimated by the N difference method were higher than the isotopic method mainly due to inclusion of previous year's N application. Several previous studies also reported lower N recoveries estimated by the isotopic method compared to the N difference method (Schiner, 1994, Cassman et al., 1993, Bronson et al., 2000, Singh et al., 2001, and Belder et al., 2005). The crop recovery of applied N as estimated by isotopic method was very low in aerobic soils (14.6% to 26.9%) compared to flooded rice. Reductions in N recovery in rice when converted to water saving systems were also observed by Eriksen et al., 1985; and Liu et al., 2010. From the amount of fertilizer N applied, 21.0% was taken by plants, 22.4% was left in the soil and 53 % was unaccounted for, indicating that N uptake was one of the major limiting factors in decreasing dry matter and subsequently the grain yields. Belder et al., (2005) also noticed higher losses of applied N in aerobic rice compared to traditional flooded conditions. The apparent N recovery in both the systems was higher at 120 kg N rate than at 180 kg N indicating that the efficiency of any input decreases with increased rate of application, because other factors become limited (DeWitt, 1992).

The N transformations in flooded rice are altogether different from aerobic rice, even though the forms of N present under both the systems are similar, the relative magnitude of nitrate and ammoniacal forms are quite different between two systems. The main N transformations in both the systems include mineralization, immobilization, ammonia volatilization, nitrification-denitrification, and leaching

In flooded soils due to submerged conditions lower mineralization rates are expected as a result of slower breakdown of soil organic matter compared to upland aerobic systems (Villegas-Pangga et al., 2000; Buresh et al., 2008). Even the immobilization rates also quite low in flooded systems due to low energy requirements of anaerobic microorganisms resulting in a high net mineralization rates. In the present study also in flooded rice 56 to 67 kg of N accumulated by the crop per hectare was derived from soil than 41.2 to 56.1 kg ha^{-1} in aerobic rice indicating that higher net mineralization rates might have the reason behind the higher uptakes in flooded rice. More over high water solubility of urea in flooded soils may also be the reason behind the high uptake rates in flooded rice plants. Due to weak adsorption of urea by soil compared to NH_4^+ (De Datta, 1981; Safeena et al., 1999) more applied urea is found in the solution phase than on the solid phase, resulting in greater absorption of urea by rice plants from flooded soil than plants in a non-flooded aerobic condition

Poor N use efficiency in aerobic rice compared to flooded systems was mainly due to increased N losses in the system. In the present experiment the unaccounted N ranged between 43 and 65% showing that most of the applied fertilizer N might have lost from the soil plant system in gaseous form. Similarly in flooded rice 34-45% of fertilizer N was unaccounted. The urea N fertilizer application in the both systems was followed by proper soil incorporation and due to quick hydrolysis of urea in soils (Savant et al., 1985) , we hypothesize minimal volatilization losses under both the systems. In the aerobic rice due to availability of oxygen in plenty and nitrification rates are generally higher. The nitrate so produced will either taken up by plant or lost to atmosphere as N_2 gas if anaerobic conditions occur (Buresh et al., 2008). In the present study also at times of irrigations and heavy rainfall events, the aerobic soils experienced frequent aerobic and anaerobic cycles which might have led to increased N losses. Therefore we hypothesize that denitrification is probably the relevant process contributing to the loss of N in aerobic rice. Even though flooded rice plots were kept submerged throughout the crop growth, mid-season aeration for promoting high tiller production might have resulted in considerable denitrification losses.

Nitrate-N in aerobic rice and ammoniacal-N in the flooded rice were the predominant forms of N leaching. Leaching losses increased in both systems with increased N rates and there were no differences in the leaching losses derived from the fertilizers between the two systems. A number of other studies also reported considerable losses through leaching in paddy soils under both aerobic and flooded systems. (Pathak et al., 2004; Zhou et al., 2009; Linquist et al., 2011; Peng et al., 2011)

Weed control is another key factor for getting optimum yields in aerobic rice. Yield losses up to 50-91% due to dry tillage, alternate wetting and drying conditions in aerobic rice were reported (Fujisaka et al., 1993; Rao et al., 2007; Singh et al., 2008). In the present experiment, up to 1.3% of applied N was taken up by the weeds. The higher growth and N accumulation by weeds in aerobic rice resulted in yield penalty in aerobic system.

The response to N in aerobic rice between two years of study was significant. The difference can be explained by the fact that during 2010, monsoon rains were well distributed and the soil moisture content was mostly maintained near field capacity throughout the crop growth. Better weed control measures using chemical herbicides were adopted and the average N uptake and N recovery by weeds was decreased to 0.8% compared to 1.2% during 2009.

In the present experiment, residual N recoveries in succeeding crops up to four seasons were determined. The results showed that the recovery of ^{15}N in the subsequent crops was very low (4.2-6.0%). Most of the residual N fertilizer recoveries occurred in the maize crop grown after rice (3-4.5 %), and decreased to 1% or less in the subsequent growing seasons indicting poor reutilization of residual N. Total recovery would increase the NUE to 26.1% and 37.0% compared to the single-season value of 21.0 and 32.2% in aerobic and flooded rice, respectively once the residual ^{15}N is also accounted for. No significant difference was observed in the subsequent crop recoveries between aerobic and flooded rice system. Similar low recoveries in succeeding crops in cropping system trials were reported by Shinde et al., 1985, Shivananda et al., 1996, Ichir et al., 2003, Sampio et al., 2004, Dourando-Neto et al., 2010 in different cropping systems. Immobilization of fertilizer N in soil organic matter that mineralizes very slow (Ichir et al., 2003) and poor synchronization between mineralization of ^{15}N labeled organic residue and crop uptake (Macdonald et al., 2002) resulted in suppressed utilization of residual N from the previously applied N. Since the residual effects are of small order, the scope of reducing N dosages for succeeding crops in the sequence keeping in view the residual N from previous application is limited.

Conclusions

The concept of aerobic rice development is to sustain the rice production in water scarce situations while producing 80-90% of yield attainable under traditional flooded rice system. The present study on response of aerobic and flooded rice to N rates showed positive response for increased N application under both the systems. However, the response to the applied N fertilizer was significantly lower in aerobic rice than in flooded rice. Consequent to the reduction in N uptake rate by aerobic rice, the apparent N recovery calculated by N difference method and N use efficiency were considerably low in aerobic rice. It suggested that a large amount of fertilizer N loss occurred from soil plant system (49%-59%) for aerobic rice. Only a small proportion of the fertilizer N applied (4.2-6.0%) to rice was recovered in succeeding maize indicating reduced residual effect under both flood and aerobic rice system. Even though residual effects were of small order, fertilizer N recoveries in soil were as high as 65 kg ha^{-1} after fourth season indicating that the contribution of applied fertilizer to the maintenance of soil fertility. Further research in aerobic rice should be directed to various ways and means by which N use efficiency in aerobic rice can be improved to make it more adaptable by the farmers.

Table 4-1. Physical and chemical soil properties of the surface (0-30 cm) profile at the experimental site measured during 2009.

Soil parameter	0 -15 cm	15-30 cm
Sand (%)	54	54
Silt (%)	13	11
Clay (%)	33	35
pH (2.5 : 1 in water)	8.0	8.2
Organic C (%)	0.51	0.48
$KMnO_4$ extractable N (kg ha^{-1})	202	189
Olsen’s extractable P (kg ha^{-1})	24.7	15.8
Ammonium acetate extractable K (kg ha^{-1})	250	167
CEC (cmol kg^{-1})	21.6	20.0

Table 4-2. Total plant N, Plant N derived from labeled fertilizer (Ndlf), non-labeled fertilizer and soil N (Nds), and labeled fertilizer remaining in soil (lnfs) in rice during 2009.

Establishment method	Applied N (kg ha^{-1})	Total N (kg ha^{-1})	Ndlf (kg ha^{-1})	Nds (kg ha^{-1})	lnfs (kg ha^{-1})
Aerobic rice	60	50.0	8.8	41.2	11.4
	120	64.0	21.8	42.2	25.4
	180	72.0	30.1	41.9	42.0
Flooded rice	60	80.5	18.7	61.8	14.2
	120	109.4	42.5	66.9	28.4
	180	120.6	58.7	61.9	48.2
ANOVA					
Method (M)		***	***	***	**
N levels (N)		***	***	NS	***
M X N		***	***	NS	NS

* P< 0.05, ** P<0.01, *** P<0.001. NS= non-significant (p>0.05).

Table 4-3. Total plant N, Plant N derived from labeled fertilizer (Ndlf), non-labeled fertilizer and soil N (Nds), and labeled fertilizer remaining in soil (lnfs) in rice during 2010.

Rice Establishment Method	N applied (kg ha^{-1})	Total N (kg ha^{-1})	Fertilizer ^{15}N uptake (N_1) (kg ha^{-1})	Fertilizer ^{15}N uptake by rice from first year ^{15}N fertilizer application (N_2) (kg ha^{-1})	Total ^{15}N uptake N_1+N_2 (kg ha^{-1})	N derived from non-labeled fertilizer and soil (kg ha^{-1})	Fertilizer ^{15}N remaining in soil (S_1) (kg ha^{-1})	Fertilizer ^{15}N remaining in soil from first year ^{15}N fertilizer application (S_2) (kg ha^{-1})	Total remaining in soil (S_1+S_2) (kg ha^{-1})
Aerobic rice	60	60.7	14.5	0.4	14.9	45.8	12.6	7.2	19.8
	120	89.3	32.3	0.9	33.2	56.1	28.6	17.0	45.6
	180	98.6	45.7	2.1	47.8	50.8	47.1	25.3	72.4
Flooded rice	60	74.6	17.5	0.7	18.2	56.4	14.7	7.8	22.5
	120	107.2	40.7	1.8	42.5	64.7	27.9	17.1	45.0
	180	123.5	56.1	1.6	57.7	65.8	51.4	25.5	76.9
ANOVA									
Method (M)		***	***	**	***	**	NS	NS	NS
N levels (N)		***	***	***	***	NS	***	***	***
MXN		NS	NS	***	NS	NS	NS	NS	NS

* P< 0.05, ** P<0.01, *** P<0.001, NS= non-significant (p>0.05).

Table 4-4. Fertilizer ^{15}N leaching and weed uptake of ^{15}N in rice during 2009.

Treatment	N applied (kg ha^{-1})	$^{15}NO_3^-$ - N (kg ha^{-1})	$^{15}NH_4^+$-N (kg ha^{-1})	% of ^{15}N fertilizer N Lost	^{15}N uptake by Weeds (kg ha^{-1})	% of fertilizer ^{15}N lost
Aerobic rice	60	0.5	0.2	1.2	0.36	0.60
	120	1.8	0.7	2.1	0.78	0.65
	180	5.7	2.0	4.3	2.34	1.30
Flooded rice	60	0.3	0.7	1.6	0.02	0.04
	120	1.5	2.4	3.2	0.06	0.05
	180	3.2	5.8	5.0	0.11	0.06
ANOVA						
Method (M)		***	***	*	***	***
N rates (N)		***	***	***	***	***
M X N		***	***	NS	***	***

* P< 0.05, ** P<0.01, *** P<0.001. NS= non-significant (p>0.05).

Table 4-5. Fertilizer ^{15}N leaching and weed uptake of ^{15}N in rice during 2010.

Treatment	N applied (kg ha^{-1})	$^{15}NO_3^-$ - N (kg ha^{-1})	$^{15}NH_4^+$-N (kg ha^{-1})	% of ^{15}N fertilizer N Lost	^{15}N uptake by Weeds (kg ha^{-1})	% of fertilizer ^{15}N lost
Aerobic rice	60	0.7	0.4	1.7	0.48	0.64
	120	2.8	1.5	3.6	0.86	0.71
	180	7.0	2.6	5.1	1.12	0.62
Flooded rice	60	0.3	0.8	1.8	0.02	0.04
	120	1.2	3.0	3.5	0.04	0.03
	180	3.6	6.6	5.6	0.05	0.03
ANOVA						
Method (M)		**	***	NS	***	***
N rates (N)		***	***	***	***	NS
M X N		***	***	NS	***	NS

* P< 0.05, ** P<0.01, *** P<0.001. NS= non-significant (p>0.05).

Table 4-6. Recovery of ^{15}N enriched fertilizer applied to rice in maize and ^{15}N in soil during 2009-10.

Treatment	Fertilizer N rate (kg ha^{-1})	Total N (kg ha^{-1})	Ndlf (kg ha^{-1})	Nds (kg ha^{-1})	Lnfs (kg ha^{-1})
AR-60 N-M-120	120	135.4	1.9	133.5	8.2
AR-120 N-M-120	120	139.8	4.9	134.9	19.7
AR-180 N-M-120	120	147.3	8.2	139.1	32.0
FR-60 N-M-120	120	121.7	1.8	119.9	10.5
FR-120 N-M-120	120	130.2	4.0	126.2	21.6
FR-180 N-M-120	120	133.3	6.5	126.8	31.4
ANOVA					
Method (M)		*	***	*	*
N levels (N)		NS	***	NS	**
MXN		NS	**	NS	*

* $P< 0.05$, ** $P<0.01$, *** $P<0.001$. NS= non-significant ($p>0.05$).

Table 4-7. Recovery of ^{15}N enriched fertilizer applied to rice by maize and ^{15}N in soil during 2010-11.

Rice Establishment Method	N applied (kg ha^{-1})	Total N (kg ha^{-1})	Fertilizer ^{15}N uptake (N_1) (kg ha^{-1})	Fertilizer ^{15}N uptake by maize from first year ^{15}N fertilizer application (N_2) (kg ha^{-1})	Total ^{15}N uptake N_1+N_2 (kg ha^{-1})	N derived from non-labeled fertilizer and soil (kg ha^{-1})	Fertilizer ^{15}N remaining in soil (S_1) (kg ha^{-1})	Fertilizer ^{15}N remaining in soil from first year ^{15}N fertilizer application (S_2) (kg ha^{-1})	Total remaining in soil (S_1+S_2) (kg ha^{-1})
AR-60 N-M-120	120	151.1	2.15	0.19	2.34	148.8	10.2	6.4	16.6
AR-120 N-M-120	120	155.3	4.96	0.45	5.41	149.9	24.9	14.1	39.0
AR-180 N-M-120	120	162.3	7.88	0.58	8.46	153.8	39.3	23.1	62.4
FR-60 N-M-120	120	136.0	2.18	0.17	2.35	133.7	11.4	6.7	18.1
FR-120 N-M-120	120	146.1	4.25	0.36	4.61	141.5	23.5	14.4	37.9
FR-180 N-M-120	120	150.2	6.60	0.48	7.08	143.1	42.0	23.1	65.1
ANOVA									
Method (M)		**	*	**	*	**	NS	NS	NS
N levels (N)		*	***	***	**	NS	***	***	***
MXN		NS	NS	NS	NS	NS	NS	NS	NS

* P< 0.05, ** P<0.01, *** P<0.001, NS= non-significant (p>0.05).

Table 4-8. Recovery fraction of ^{15}N enriched fertilizer N applied to rice in succeeding crops in rice-maize sequence during 2009 and 2010.

Treatment	Recovery by maize plant (2nd crop)	Recovery in soil after maize		Recovery in rice crop(3rd crop)	Recovery in soil after rice		Recovery in Maize crop (4th crop)	Recovery in soil after Maize	
		0-15 cm	15-30 cm		0-15 cm	15-30 cm		0-15 cm	15-30 cm
Aerobic- 60 N	3.23	12.8	0.8	0.69	11.0	0.65	0.32	10.4	0.32
Aerobic- 120 N	4.10	15.2	1.2	0.78	13.2	1.00	0.38	11.2	0.56
Aerobic- 180 N	4.50	16.4	1.4	1.14	12.8	1.20	0.32	12.0	0.82
Flooded-60 N	3.03	16.2	1.2	1.24	12.1	0.80	0.28	10.8	0.46
Flooded-120 N	3.34	17.2	0.8	1.53	13.6	0.64	0.30	11.4	0.58
Flooded-180 N	3.63	15.8	1.6	0.88	13.2	0.92	0.27	12.1	0.71
ANOVA									
Method (M)	***	**	NS	***	NS	NS	**	**	NS
N rates (N)	***	**	**	*	**	NS	NS	*	NS
M X N	NS	**	**	***	NS	NS	NS	*	NS

* P< 0.05, ** P<0.01, *** P<0.001, NS= non-significant (p>0.05).

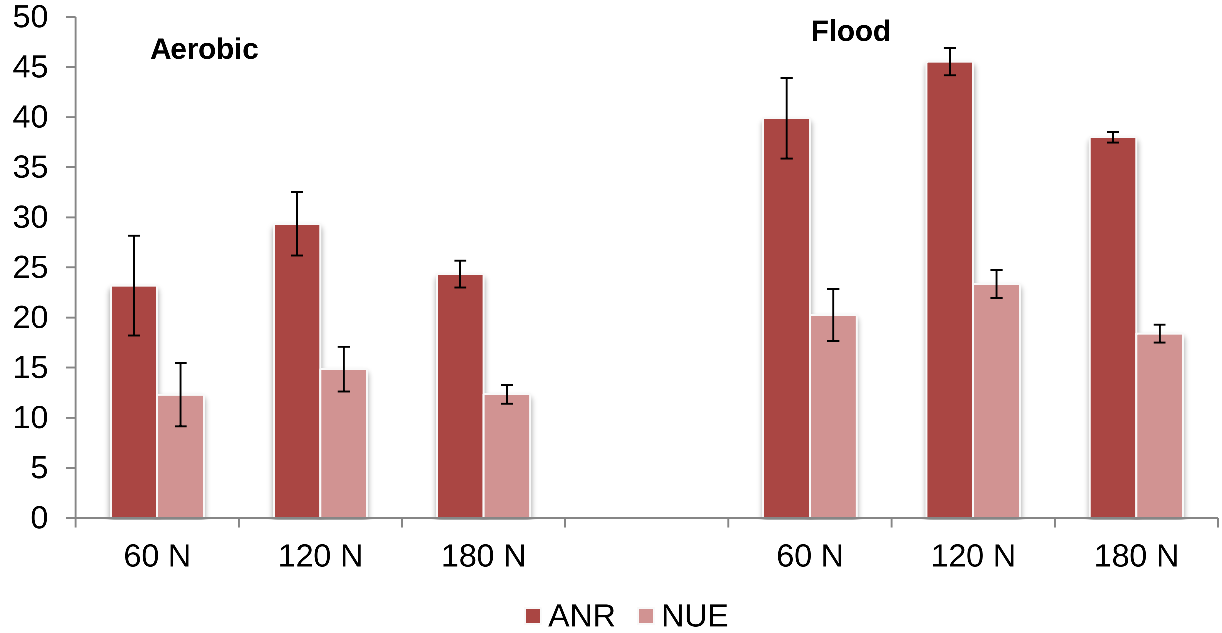


Figure 4-1. Apparent N recovery (%) and N use efficiency (kg grain kg N applied^{-1}) of rice as influenced by N rates under aerobic and flooded conditions.

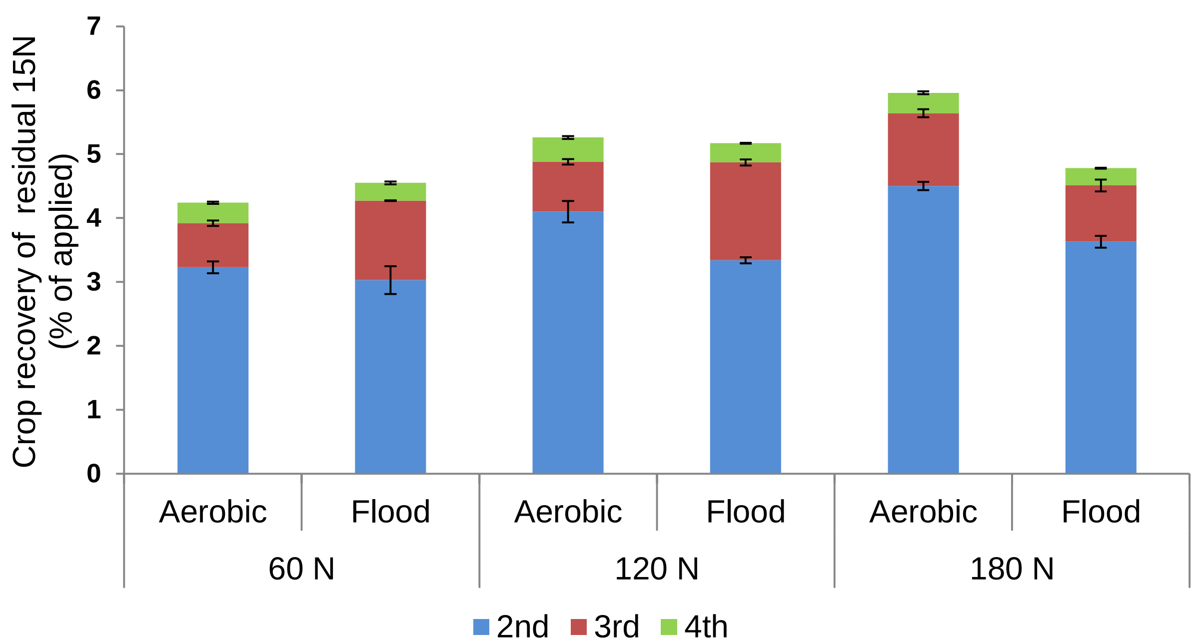


Figure 4-2. Average ^{15}N in crop derived from a single application of N labeled fertilizer to rice under different N rates in subsequent growing seasons. The legend refers to the number of growing seasons after application.

CHAPTER 5
APPLICATION OF CSM-CERES-RICE AND MAIZE MODELS FOR EVALUATION OF IRRIGATION AND NITROGEN MANAGEMENT IN RICE-MAIZE CROPPING SYSTEM FOR SEMI ARID TROPICS.

Background

Rice- maize double cropping (R-M) is the most important emerging system in South Asia. The R-M systems currently occupy around 3.5 M ha in Asia (Timsina et al., 2010). The recent water shortage conditions for continuous rice cultivation have prompted studies to look for alternate rice-based cropping systems. The development of short duration rice varieties coupled with high yielding maize hybrids provided an opportunity for increasing the area under R-M cropping in this region. Since both crops in R-M sequences are high nutrient input intensive crops due to their large grain and by-product yields, both extract high amounts of nutrients from the soil. Hence proper nutrient management strategies should be developed for R-M systems with an aim to supply adequate fertilizers based on demand, minimize nitrogen (N) losses and maximize nutrient use efficiency. Field experiments conducted in R-M sequences mostly focused either on rice or maize independently without considering the influence of the previous crop and its associated growing conditions. Stand establishment in maize grown in an R-M sequence is influenced to a great extent by soil moisture content and soil physico- chemical conditions after rice as maize is typically grown immediately after rice without land preparation. However, conducting field experiments in cropping systems for quantifying optimal crop N and water requirements are time consuming, requiring many resources and years to draw valid conclusions.

Crop simulations models consider the complex interactions among crop, weather, soil and management factors that will influence crop performance. The crop simulation models may be very useful in identifying the best management strategies for a crop rotation using soil and weather parameters (He et al., 2011). Crop growth models such as DSSAT have been used successfully in many places around the world for a wide range of conditions and applications (Tsuji et al., 1998; Jones et al., 2003; Hoogenboom et al., 2010). The Decision Support System for Agro technology transfer (DSSAT) is a package of 16 crop growth models derived from DSSAT-CROPGRO and CERES models that uses the soil, weather and crop management files to predict the crop growth and yield (Jones et al., 2003). CERES (Crop Estimation through Resource and Environment Synthesis) Rice and Maize models embedded in DSSAT are process based models that simulate the main processes of crop growth and development such as phenological events, the development of canopy to intercept photosynthetically active radiation and its use to accumulate dry matter. The CERES-Rice and Maize models were evaluated by many researchers across locations for phenology, growth and yield (Thornton et al., 1995; Wafula, 1995; Kiniry et al., 1997; Ritchie et al., 1998; Jagtap et al., 1999; Singh et al., 1999; Sarkar and Kar, 2006; Timsina and Humphreys, 2006; O'Neal et al., 2002) with good agreements between predicted and observed values. Some studies using these simulation models were initiated to increase the resource use efficiency of cropping systems (Timsina and Connor, 2001; Sarkar and Kar, 2006; Timsina and Humphreys, 2006). Even though most of the studies evaluated the DSSAT CERES-Rice and Maize models for crop growth and yield predictions for their own local conditions, none of the studies reported on the prediction of rice and maize yields in response to changes in rice establishment methods from traditional flooded method to water saving aerobic rice and associated N and water balances. In addition, studies on alternative irrigation management practices in rice-maize system using long-term weather data to reduce water requirements were not conducted earlier. The main objectives of this study were to 1) evaluate the DSSAT cropping system model for its prediction of soil water, N balance and rice yields in response to methods of rice establishment and N rates in R-M cropping system, and 2) determine best management options to increase water productivity of aerobic R-M system for semi-arid tropics using long term weather data.

Materials and Methods

Experimental Site

Field experiments were conducted during 2009 to 2011 at the experimental farm of Acharya NG Ranga Agricultural University, Hyderabad, India. The experimental site was located in the Southern Telangana Agro climatic zone of Andhra Pradesh, India (17°19' N, 78°28' E and 534 m above mean sea level). The soil at the experimental site was a sandy loam soil. The physico-chemical characters of the soil at the experimental site used for model calibration, evaluation and application are presented in Table 5-1.The climate of the area is semi-arid in nature with annual rainfall of 850 mm (80% of which is received during the south west monsoon period (June – October).

Treatment Details

Rice and maize crops were grown in a rice-fallow-maize-fallow sequence. Rice was grown during the monsoon season from July to October and maize was grown in the dry season from November to March. The design of the experiment was split plot with rice establishment methods as the main plots and four N rates as subplot treatments within the main plots. The two rice establishment methods were aerobic and flooded rice and the four N treatments were 0, 60, 120 and 180 kg N ha^{-1}. Nitrogen was applied in three split rates, at the time of planting, at maximum tillering and at panicle initiation stages in both aerobic and flooded plots. MTU 1010, a popular high yielding variety, was selected for rice under both aerobic and flooded method. The rice seed was directly planted in rows 22.5 cm apart in the first week of July for aerobic rice treatments. The aerobic rice was irrigated with 50 mm of water whenever the soil moisture tension at top 10 cm reached -30 kPa using Delta-T Devices- ML2 capacitance probe. In flooded rice treatments, a seedling nursery was planted on the same day when the aerobic rice crop was planted. After 30 days, seedlings were transplanted at a spacing of 20 X 15 cm keeping two seedlings per hill. After rice harvest, DeKalb 800 M variety of maize was planted at a spacing of 60 x 20 cm under no tillage conditions. The maize crop was irrigated with 50 mm water timed at irrigation water/cumulative pan evaporation ratio (IW/CPE) of 1.0. The maize crop received 120 kg N, 26 kg P and 33 kg K ha^{-1}. Fertilizer N was applied in three splits, at the time of planting, at knee height stage and at silking whereas all P and K were applied at the time of planting.

Measurements

Weather data (maximum and minimum temperatures, rainfall, and sunshine hours) were taken from the meteorological observatory at Agricultural Research Institute (ARI), Rajendranagar, Hyderabad located at 100 m distance from the experimental plot. The daily bright sunshine hours were converted to solar radiation (MJ m^{-2} day^{-1}) using the DSSAT Weatherman sunshine hours to solar radiation conversion from the Angstrom Formula (Allen et al., 1998). The soil parameters, such as soil texture, soil pH, bulk density, drained upper (DUL) and lower limits (DLL) hydraulic conductivity and organic carbon were estimated using International pipette method (Piper, 1966), Beckman pH meter (Jackson, 1967), core sampler method, pressure plate apparatus, constant-head method and Wet digestion method (Walkley and Black, 1934), respectively. Observations on phenological events, leaf area index, dry matter accumulation, N content in plants were taken at regular intervals. Soil moisture content was measured at weekly intervals using Delta-T Devices theta probe with a PR2 sensor, a multi-sensor capacitance probe which consisted of a scaled polycarbonate rod with six pairs of stainless steel rings centered at 10, 20, 30, 40, 60 and 100 cm.

Model Calibration and Evaluation

The CERES-Rice and CERES- Maize models available with DSSAT v 4.5 (Hoogenboom et al., 2010) were used in the study. Model calibration involves adjustment of coefficients for a genotype so that a best fit can be obtained between observed and predicted values. The CERES-Rice model was calibrated with the data obtained from the 2009 field experiment with the treatment grown under flooded conditions receiving 120 kg N ha^{-1} as it is important to use treatments that have minimum soil constraints to production when estimating cultivar parameters (Jones et al., 2010). On the other hand, the CERES-Maize was calibrated with the treatment that followed the flooded rice receiving 120 kg N ha^{-1}. The cultivar coefficients were determined using Generalized Likelihood Uncertainty Estimation (GLUE) method (Beven and Binley, 1992; Franks et al., 1998; Shulz et al., 1999; Jones et al., 2010). In this method, the parameter space is first discretized by generating a large number of parameters values from the prior distribution. Likelihood values are then calculated at each parameter value using differences between model predictions and measurements. Weights and probabilities are calculated with the Bayesian equation, and the posterior parameters are estimated. After estimating the cultivar coefficients for rice and maize, the models were next evaluated by comparing observed and predicted results for the remaining treatments in 2009. The phenological observations such as days to anthesis and maturity, measured crop yield, biomass were also used to calibrate and evaluate the models. Finally, the model predictions were evaluated using independent data from the experiments conducted in 2010.

Statistics

The performance of the model was evaluated using the coefficient determination (R^2), absolute and normalized root mean square error (RMSE), and the Wilmot d index. The values of RMSE and d -index determine the capability of the model in predicting the experimental data. Lower RMSE and a d-value close to one indicate better agreement between the experimental data and modeled output. The normalized RMSE (%) indicates the relative difference between simulated and observed values. In this paper, the model simulations were considered excellent, good, fair, and poor based on the respective normalized RMSE (NRMSE) values of <10%, 10-20%, 20-30%, and >30% (Loague and Green, 1991). The modeling efficiency (ME) compares modeling variability with experimental variability. A negative ME value means that the modeling variability is higher than the experimental variability, and thus indicates that simulations are not satisfactory. The computation methods and equations for the model performance measures are

RMSE (Wallach and Goffinet, 1987) $=\left[n-1\sum_{i=1}^{n}(Pi-Oi)^2\right]^{0.5}$ (5-1)

Where P_i and O_i are the predicted and observed values, n is the number of observations

Normalized RMSE (%) = $\left(\frac{absolute\ RMSE}{\bar{O}}\right)X\ 100$ (5-2)

$\bar{O}$= average observed value

d-index (Willmott et al., 1985) $=1-\left[\frac{\sum_{i=1}^{n}(Pi-Oi)^2}{\sum_{i=1}^{n}\left[\left|P_i'\right|+\left|O_i'\right|\right]^2}\right]$ (5-3)

Modeling efficiency (Garnier et al., 2001) $= \frac{\left[\sum_{i=1}^{n}(Oi-\overline{O})-\sum_{i=1}^{n}(Pi-Oi)^2\right]}{\sum_{i=1}^{n}(Oi-\overline{O})^2}$ (5-4)

Model Application- Seasonal Analysis

After successful calibration and evaluation of the model, the seasonal analysis option of DSSAT, which has the ability to analyze and compare the different management options, biophysically and economically, for selecting the most efficient management options using historical weather data was utilized to simulate the effects of weather variability on yields for irrigation and N scenarios in aerobic rice. Fourteen scenarios featuring different irrigation, N rates, and N application times were simulated. Also included in the simulation analysis was a potential yield scenario, created by turning off the water and N modules of CERES-Rice to know the potential yield under aerobic rice with the present varieties. Similarly for maize, nine scenarios with different irrigation and N rates, including one potential production scenario, were simulated. The irrigation treatments in aerobic rice were implemented with automatic irrigation of 40 mm being applied when available soil water was less than or equal to 60, 80 or 100% of what the soil can hold in the top 30 cm of the profile. In the field experiments, the irrigations were applied at -30 kPa (DUL) with 50mm irrigation water, which almost equals to automatic irrigation at 100% available soil water (ASW). The N rates tested were 120 and 180 kg N ha^{-1} applied in either three or four splits. In case of maize, automatic irrigation of 30 mm was implemented when the simulated available soil water was less than or equal to 20, 30, 40 and 50% of what the soil could hold in the top 30 cm of the profile. Two N rates of 120 and 180 kg ha^{-1} applied in three splits were used for maize management options. Simulations were performed for the period 1985-2009 (25 years) using the climatic data collected from weather station, ARI, Rajendranagar, Hyderabad. The scenarios were analyzed in terms of yield, water and N dynamics and the best four scenarios in flooded, aerobic rice and best two scenarios in maize were identified for crop rotation analysis. In DSSAT, the Priestley-Taylor method was used for estimating evapotranspiration and the CENTURY method was used for soil organic matter (SOM) simulations. The DSSAT-CENTURY model was initialized by providing estimates of the fraction of stable organic carbon (SOM3 fraction) in the soil based on the field history data. Once stable C (SOM3) has been estimated, the fractions of SOM1 and SOM2 are assumed to be 5% and 95% of the remaining amount, respectively (Porter et al., 2009).The results of various management scenarios were compared with biophysical and strategic analysis of yields, N and water balance components by cumulative probability function plots, cumulative density function, percentile distribution, and mean variance analysis (E-V).

Sequence Analysis

Crop yields, N and water balance of the rice-fallow-maize-fallow sequential system were simulated using the sequential analysis module of DSSAT. In this analysis, rice was planted in the rainy season and was followed by maize in the post rainy season. The program allows users to study the long term effects of R-M cropping systems on soil fertility, water balance and yield stability. In the present study, the scenarios that were found effective in seasonal analysis of rice and maize were run in four sequences, each of flooded rice-fallow-maize-fallow and aerobic rice-fallow-maize-fallow sequence, to identify the most suitable rotation with best combination of management options. The treatment combinations involving aerobic and flooded rice followed by maize were presented in Table 5-4. The sequences were run for 25 years using the historical weather data from 1985-2009. The simulated results on crop yields, N uptake, leaching, and water balance components were analyzed using various statistical parameters. Stability analysis was carried out on crop yield to identify the crop sequence with minimum variability across different years. Four stability indicators used in this study were

The variance (S_i^2) of a system = $\sum_{j=1}^{q} \frac{[Xij - \bar{x\imath}]^2}{q-1}$ (5-5)

The variance indicates the variability in the yield from mean yield of the particular cropping system

Coefficient of variation (CV_i) = $\left[\frac{Sj}{\overline{X\imath}}\right]$ X 100 (5-6)

CV is the coefficient variation of i^{th} system and Si and $\overline{X\imath}$ are the standard deviation and grand mean of the system over years.

Wrickie's (1962) Ecovalance considers the cropping system and year interaction mean-squares for stability analysis. Smaller Wi2 values indicate more stable system and vice versa

Wrickie's Ecovalance (Wi^2) = $\sum_{j=1}^{q}[X_{\mathrm{ij}} - \bar{X}_{\mathrm{i.}} - \bar{X}_{\mathrm{.j}} + \bar{X} \ldots.]^2$ (5-7)

Wi^2 the ecovalance parameter of i^{th} cropping systems tested in different years

Finlay & Wilkinson's (1963) was estimated by regressing observed yields of the cropping systems with an environmental index, defined as the difference between the marginal mean yield of the environments and the overall mean

Finlay & Wilkinson's regression coefficient (β_i) $= \frac{\sum_{j=1}^{q} X_{\mathrm{ij}}\, \bar{X}_{\mathrm{.j}} - \frac{\bar{X}_{\mathrm{i.}}\,\bar{X}}{q}}{\sum_{j=1}^{q} \bar{X}_{\mathrm{.j}}{}^2 - \frac{\bar{X}^2}{q}}$ (5-8)

β_i is the regression coefficient of cropping system i.

Results and Discussion

Model Calibration

The CERES-Rice and CERES-Maize models were calibrated with the experimental data collected during 2009. The calibrated genetic coefficients were derived by the GLUE method and comparison of model observed and simulated data. The final genetic coefficients derived for rice cultivar MTU 1010 and Maize cultivar DeKalb 800M are presented in the Tables 5-2 and 5-3. The calibration was initially carried out with best treatment tested and the simulated and observed values of days to anthesis, maturity, grain, biomass, yield, and N uptake are presented in the Table 5-5. A close agreement was observed between the simulated and observed values for phenology, grain yield and N uptake in both crops. The data collected from the remaining treatments in rice were also used to check the accuracy of the model during 2009.The statistical indices (RMSE and modeling efficiency) used to evaluate the accuracy of the model are presented in Table 5-6. The model was able to predict the phenological events (days to anthesis and maturity), grain yield, tops weight, and N uptake fairly well in both aerobic and flooded rice establishment methods with NRMSE of 14.5%, d- values of 0.93 and with a modeling efficiency of 0.73. However, the model under predicted leaf area index and over-predicted the soil moisture content, suggesting poor modeling efficiency. The model has shown the ability to simulate grain yield under various N rates under different establishment methods as indicated by high r^2 values.

Model Evaluation

The CERES-Rice and Maize model were evaluated for phenology, growth, grain and straw yields using the experimental data collected during the 2010-11 season.

Phenology and growth

The model predicted the phenological events of anthesis and maturity in rice and maize accurately with low RMSE (2.0) and high d-index (0.90). Simulated and observed values of above ground biomass at various growth stages for different N rates under both aerobic and flooded rice conditions were found to be superior with acceptable NRMSE (23%) and high “d” (0.97) and “r” (0.95) values. Simulations for LAI were poor as model under predicted the LAI most of the times. The predictions were better for higher N rates than the lower rates (Table 5-7).

Changes in soil water content during the aerobic rice crop growth were well simulated by the model at 15 and 30 cm depth with an overall NRMSE of 15.5% and d-index of 0.56. The model slightly over-predicted the soil moisture content during the drought year of 2009 and under-predicted during a well distributed monsoon period of 2010 (Figure 5-1). Overall, the soil water content simulations were in good agreement with the observed data (RMSE=0.05, d=0.56 and r=0.9).

Grain yield

There was good agreement between the predicted and observed grain yields both in rice and maize crops. The models predicted the grain yields of aerobic and flooded rice quite well with RMSE of 0.57 t ha^{-1}, NRMSE of 10.3, ME of 0.87 and a d- values of 0.97 (Table 5-6). Similarly, maize grain yields were also simulated by the model reasonably well with RMSE of 0.23 t ha^{-1}, NRMSE of 3.6% and d-values of 0.71 (Table 5-8). The model evaluation indicated that CERES-Rice model can simulate rice phenology, growth and yield in various rice crop establishment (aerobic and flood) systems accurately.

Model Application- Seasonal Analysis

Seasonal analysis was carried out to identify the optimum management options for irrigation and N for aerobic, flooded rice and maize for single seasons each taking in to account seasonal climate variability but not rotational influences of soil water and N carry over.

Grain yield and N uptake

The outputs obtained from the analysis for different irrigation regimes and N rates are presented in Table 5-9. The analysis predicted grain yields of 7.96 t ha^{-1} under non-limiting (potential) conditions in aerobic rice, indicating that there is scope in aerobic rice to achieve higher yields if all the limiting factors especially water, weeds and nutrient stresses are eliminated. In aerobic rice identification of optimum irrigation regimes are crucial for high yields. Use of an automatic irrigation option in aerobic rice by changing the available soil water to less than or equal to a value of 60, 80 and 100% of what the soil can hold in the top 30 cm of the profile resulted in significant yield differences. Changing the threshold from 60% to 80% or 100%, resulted in yield reduction coupled with high leaching losses of N, indicating that the 60% threshold level was optimum for aerobic rice. Higher water productivity also occurred in 60% threshold level. Mean grain yields of aerobic and flooded rice increased when the rate of N was increased from 120 kg to 180 kg ha^{-1}. Similar increases in simulated yields by the CERES-Rice model under increased rates of N was also reported by Aggarwal et al., 1997, Sarkar and Kar, 2006. Nitrogen uptake also followed a similar increasing pattern in both aerobic and flooded rice with the increase in N fertilizer rates. Increasing the number of split applications of N fertilizers from three to four in aerobic rice showed a considerable increase in yields and reduction in N leaching, suggesting an advantage of splitting applications of N. The strategic analysis using percentile and cumulative function plots to identify the best scenario showed that application of 180 kg N in four splits and irrigation at the 60% threshold level in aerobic rice resulted in the highest yields among all management options tested (Figure 5-2). In flooded rice, application of 180 kg ha^{-1} was found to be more efficient. Even the E-V plots demonstrated the superiority of 180 kg N in both aerobic and flooded rice, showing high mean and low variance for these scenarios.

Drainage and N leaching

Unlike the traditional flooded system of rice production, the soil in aerobic rice is well aerated and therefore N leaching is of considerable importance as most of the N is available in nitrate form. Drainage occurs when irrigation supply exceeds water holding capacity of the soil. In the aerobic rice scenario, irrigating at 100% ASW resulted in significantly higher amount of drainage (656-685 mm) compared to irrigating at 60% ASW (224 to 238 mm). When drainage was high, leaching was also high indicating that N leaching was greatly influenced by irrigation threshold rates in aerobic rice. Increased irrigation thresholds also increased N leaching losses. The probability to exceed 64 kg of leached N ha^{-1} $crop^{-1}$ was about 20% in the 60% threshold and 52% in 80% threshold (Figure 5-3). In flooded rice, due to anaerobic conditions the leaching losses were very low. Rinaldi et al., 2007 also reported similar results from seasonal analysis of tomato where higher N leaching associated with higher drainage was observed.

Maize

The plots of percentile distribution and cumulative functional plots showed that application of 120 kg N ha^{-1} and irrigations with 30 mm at 40% ASW showed maximum yields at all cumulative probability percentage values. This indicates a first order dominance of this treatment. The E-V plots showed that scenario 3 (90 N and 40%

ASW), 5 (120 N and 30% ASW) and 6 (120 N and 40% ASW) were superior to others (Figure 5-4).

Sequence Analysis

Sequence analysis was conducted to identify the best management options using the scenarios found to be the best in seasonal analysis (four scenarios in rice and two in maize). Various stability indices were used to identify the most stable R-M cropping system. The sequence analysis was run with 25 years of historical weather data from 1985-2009.

Yield and water productivity

The sequence analysis output indicated that the highest predicted average yields in aerobic rice can be obtained with application of 180 kg N ha^{-1} and 40 mm irrigation at 60% ASW. This system produced 96% of the yields produced by flooded rice system with 38% saving in irrigation water (Table 5-11). For the overall R-M system the highest yields were obtained with flooded rice receiving 180 kg N ha^{-1} followed by maize with 120 kg N. Application of 90 kg N to maize was found to be equally good and reducing N rate was not associated with reduction in yields of maize. Even though application of 180 kg N for aerobic rice resulted in the highest yield, this treatment may have environmental risks because of higher nitrate leaching losses (66 kg N ha^{-1} crop^{-1}) compared to 120 kg N application (43 kg N ha^{-1} crop^{-1}). Water productivity (WP) g grain kg of water^{-1}, (average of all aerobic rice treatments) as estimated from the grain yield and amount of water used (irrigation + rainfall) was higher with aerobic rice (0.84) and aerobic R-M system (1.15) compared to flooded rice (0.50) and flooded R-M system (0.79).

Water balance components of rice-maize system

Water balance components were simulated under different rice establishment methods to assess the impact of aerobic rice. Significant differences were observed in various water balance components between the aerobic and flooded rice systems. Aerobic rice averaged 872 mm of water over the 25 years compared to 1417 mm in flooded rice, resulting in 38.4% saving. It was found that irrigated water in flooded rice was lost mostly through deep percolation since the seasonal evapotranspiration was approximately the same under both systems (Table 5-12). Irrigation requirements and water balance components of rice-fallow-maize crop was not influenced by the rice establishment method.

Nitrogen balance components of rice-maize system

Crop establishment methods such as aerobic rice will have a strong influence on N dynamics in rice since the crop is grown under oxic conditions compared to traditional anaerobic, flooded rice. In order to study the influence of the aerobic rice, N balance components were simulated under varying N rates in both the systems. Fertilizer application played a major role in increasing rice yields under both systems and N output primarily occurred during crop harvest. Rice crop obtains majority of its N requirement (60-80%) from the organic N pool of the soil (Broadbent, 1979) and therefore the amount of N mineralized during the crop season is also important for achieving higher yields. In flooded soils, soil organic matter decomposition is slow due to anaerobic conditions. This was also clearly indicated by the simulated results on mineralized N which showed that on average, 78% more N was mineralized and available to the crop in aerobic rice compared to flooded system. On the other hand, most of the N lost in flooded rice was mainly through denitrification and, to a small extent, volatilization and leaching (Table 5-13). The differences in various N components were mainly due to the system of rice cultivation, as in aerobic rice nitrate-N is the dominant form and can be easily leached from the system if not utilized. Nitrogen losses in rice-fallow-maize were not influenced greatly by rice establishment methods however increased N rates in rice led to increased N losses in maize. The leaching losses of N were more in maize grown after aerobic rice than after flooded rice mainly due to higher mineralization rates in aerobic rice-maize systems.

Stability analysis of rice-maize system

Yield stability of cropping systems may be more important than yield maximization. Stability indicates the variability of cropping systems across different environments. The cropping systems with minimum variability are regarded as stabilized systems. Various stability indices were used to identify the best cropping system. In this study, FR with 120 kg N ha^{-1} followed by maize with 120 kg N ha^{-1} were found to be more stable system as with smaller variance. Wrickie's ecovalance (W_i^2) given by Eq. (5-7) considers the cropping system and year interaction mean-squares for stability analysis. Smaller W_i^2 values indicate more stable system and vice versa. According to this criterion, the AR with 180 kg N ha^{-1} followed by maize with 120 kg N ha^{-1} was found to be the best system. The observed yields of the cropping systems were also regressed with an environmental index, defined as the difference between the marginal mean yield of the environments and the overall mean, in order to estimate the regression coefficient (β_i). The βi for each cropping system was considered as a measure of stability with the β_i values ≥ 1 considered as stable systems. According to this criterion, the FR with 180 kg N ha^{-1} followed by maize with 120 kg N ha^{-1} was found to be the best system. The Coefficient of variation (CV %) indicated that the FR with 180 N ha^{-1} followed by maize with 90 kg N ha^{-1}was the most stable system. Even though different parameters suggested different results, the overall rank sum indicated that the FR with 180 kg N followed by maize either with 120 kg N ha^{-1} or 90 kg N ha^{-1} was found to be the stable cropping systems (Table 5-14). Among the aerobic rice systems, AR with 180 kg N followed by maize with either 120 kg N or 90 kg N ha^{-1} systems were found to be the most stable systems. Overall, the sequence analysis and stability indices indicated that in both aerobic and flooded rice systems application of 180 kg N ha^{-1} to rice followed by maize with 120 kg N ha^{-1} were the most stable systems.

Conclusions

The DSSAT CSM- CERES-Rice and Maize models were successfully calibrated and evaluated as a research tool to identify the best management options for the rice–maize cropping system in semi-arid tropics of India. The CERES-Rice and Maize models generally produced good predictions of grain yield, aboveground biomass and N uptake across a range of N and water management regimes. The performance of the model in simulating growth and yield was relatively higher with N application treatments than with no N treatments.

Different scenarios were developed and tested using the seasonal analysis module of DSSAT with the historical data to investigate the effect of irrigation and N fertilizer rates on harvested yield, water productivity and N uptake in rice and maize crops. The analyses clearly demonstrated that the yield level of aerobic rice can be improved almost to the yield level of the flooded system while saving substantial amount of water by careful water and fertilizer management strategy. However, if the N application rates exceed actual crop requirements it may result in high N leaching as shown by the model simulations. Based on the simulations, it can be concluded that application of 180 kg N ha^{-1} in four split applications and irrigation at 60 % ASW were the best management options for aerobic rice. The highest yield of maize crop was obtained with application of 120 kg N ha^{-1} and irrigations given at 40% ASW. The results nearly replicated the experimental results with enhanced responses to increased N fertilizer rates under both the establishment methods. In the field experiments, irrigation to the aerobic rice were given with 50mm at -30 kPa, which equals to 100% ASW and CERES-Rice predicted almost similar yields with this irrigation scenario. Further, the DSSAT analysis showed that careful maneuvering of irrigation and N inputs by changing the irrigation threshold and increasing the split applications of N can improve the aerobic rice yields on par with flooded rice.

The sequence analysis showed that in semi-arid conditions, adoption of aerobic R-M system can save water thus reduce groundwater pumping rates. Marginal increase in yields and N uptake were observed in maize that followed aerobic rice than in maize that followed flooded rice. The results also indicated that application of a high rate of N fertilizer in rice (180 kg ha^{-1}) can save N application rate in the succeeding maize crop without reducing the yield. The simulation results were in agreement with field experimental results that showed that approximately 8-10 kg of N applied to rice was taken by the succeeding maize. Based on the long-term simulations for 25 years, it can be concluded that the stability in production of R-M cropping system can be maintained over a long period with the application of 180 kg N ha^{-1} in rice followed by 120 kg N ha^{-1} in maize under both aerobic and flooded rice systems. Our study also showed that the DSSAT can be useful to assist in identification of the best management system for R-M systems. Sarkar and Kar (2006) also reported the usefulness of simulation models in identifying the best N management rates in rice-wheat system. Similarly Rinaldi et al. (2007), Sarkar and Kar (2008), Timsina et al. (2008), and Behera and Panda (2009) used the seasonal and sequential analysis options of DSSAT to decide optimal N and water regimes for wheat, tomato, rice-wheat and wheat crops respectively.

Finally, it should be noted that simulation results presented in this study have some uncertainties associated with inputs and model parameters, which may affect the model predictions to some degree. Furthermore, it should also be noted that the numerical simulation model does not account for the influence of weeds, pest and diseases on crop growth and development. The CERES-Rice also does not consider the spikelet sterility during moisture stress at flowering which, under moisture stress conditions, may result in over estimation of yields especially in aerobic rice.

Table 5-1. Physical and chemical properties of the experimental plot used in model evaluation and application.

Depth	LL (cm^3 cm^{-3})	DUL (cm^3 cm^{-3})	SAT (cm^3 cm^{-3})	SRGF	BD (g cm^{-3})	SOC (%)	Clay (%)	Sand (%)	Silt (%)	pH	CEC (cmol kg-$^{1)}$
0-15	0.13	0.23	0.42	1.00	1.37	0.51	33.4	53.6	13	8.0	26.9
15-30	0.15	0.24	0.43	0.90	1.42	0.48	35.4	53.6	11	8.2	18.0
30-45	0.14	0.26	0.42	0.70	1.56	0.34	33.4	59.6	7	8.2	13.3
45-60	0.08	0.23	0.36	0.30	1.53	0.14	25.4	65.6	9	8.1	9.0
60-75	0.10	0.24	0.37	0.10	1.44	0.31	31.4	60.6	8	8.1	8.4
75-90	0.13	0.23	0.38	0.02	1.56	0.04	21.4	69.6	9	8.2	5.1
90-105	0.08	0.26	0.40	0.01	1.59	0.08	27.4	65.6	7	8.2	6.6
105-120	0.08	0.24	0.41	0.01	1.49	0.08	21.4	67.6	11	8.2	6.9
120-135	0.09	0.24	0.40	0.01	1.69	0.11	21.4	76.6	2	8.4	5.5
135-150	0.08	0.20	0.38	0.01	1.52	0.07	18.4	75.6	6	8.5	4.7

Table 5-2. Genetic coefficients developed for rice variety MTU-1010.

Genetic parameters	Description	Coefficient for MTU-1010
P1	Time period (expressed as growing degree days [GDD] in ^oC above a base temperature of 9 ^oC) from seedling emergence during which the rice plant is not responsive to changes in photoperiod. This period is also referred to as the basic vegetative phase of the plant	407.0
P20	Critical photoperiod or the longest day length (in hours) at which the development occurs at a maximum rate. At values higher than P20 developmental rate is slowed, hence there is delay due to longer day lengths	173.0
P2R	Extent to which phasic development leading to panicle initiation is delayed (expressed as GDD in ^oC) for each hour increase in photoperiod above P20.	367
P5	Time period in GDD (^oC) from beginning of grain filling (3–4 days after flowering) to physiological maturity with a base temperature of 9^oC.	11.7
G1	Potential spikelet number coefficient as estimated from the number of spikelets per g of main culm dry weight (less lead blades and sheaths plus spikes) at anthesis. A typical value is 55.	61.3
G2	Single grain weight (g) under ideal growing conditions, i.e. non- limiting light, water, nutrients, and absence of pests and diseases.	0.022
G3	Tillering coefficient (scalar value) relative to IR64 cultivar under ideal conditions. A higher tillering cultivar would have coefficient greater than 1.0.	1.0
G4	Temperature tolerance coefficient. Usually 1.0 for varieties grown in normal environments. G4 for japonica type rice growing in a warmer environment would be 1.0 or greater. Likewise, the G4 value for indica type rice in very cool environments or season would be less than 1.0.	1.11

Table 5-3. Genetic coefficients developed for maize variety DeKalb 800 M.

Genetic parameters	Description	Coefficient for DeKalb 800M
P1	Thermal time from seedling emergence to the end of Juvenile phase during which the plants are not responsive to changes in photoperiod (degree days).	176.6
P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at maximum rate, which is considered to be 12.5 h (days).	0.650
P5	Thermal time from silking to physiological maturity (degree days).	885.0
G2	Maximum possible number of kernels per plant	531.0
G3	Grain filling rate during the linear grain filling stage and under optimum conditions (mg/day).	8.5
PHINT	Phyllochron interval (degree days).	60.0

Table 5-4. The treatment combinations used for sequence analysis simulations.

Scenario	Rice		Maize	
	N	Irrigation	N	Irrigation
AR-120-M-120	120 kg N ha^{-1} in four splits	40 mm when ASW in top 30 cm equaled 60%	120 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
AR-120-M-90	120 kg N ha^{-1} in four splits	40 mm when ASW in top 30 cm equaled 60%	90 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
AR-180-M-120	180 kg N ha^{-1} in four splits	40 mm when ASW in top 30 cm equaled 60%	120 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
AR-120-M-90	180 kg N ha^{-1} in four splits	40 mm when ASW in top 30 cm equaled 60%	90 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
FR-120-M-120	120 kg N ha^{-1} in three splits	Flood conditions	120 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
FR-120-M-90	120 kg N ha^{-1} in three splits	Flooded conditions	90 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
FR-180-M-120	180 kg N ha^{-1} in three splits	Flooded conditions	120 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
FR-120-M-90	180 kg N ha^{-1} in three splits	Flooded conditions	90 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%

AR- Aerobic rice; FR- Flooded rice; M-Maize; ASW –Available soil water.

Table 5-5. Simulated and observed phenological dates, growth characters and grain yield of rice and maize during 2009-10 in flooded rice-120 kg N and Maize fallowed by flooded rice with 120 kg N treatments.

Crop-variety	Anthesis (DAP)		Maturity (DAP)		Tops weight (t ha^{-1})		Grain N at maturity (kg ha^{-1})		Tops N at maturity (kg ha^{-1})		Unit grain weight (g)		Grain yield (t ha^{-1})	
	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim
Rice MTU-1010	95	96	127	128	12.3	12.2	75.6	83	109	113	0.02	0.02	5.9	6.0
Maize DeKalb 900 M	66	67	115	114	11.1	13.3	88.0	89	130	115	0.28	0.27	5.7	5.6

Sim - simulated; Obs- Observed; DAP- Days after planting.

Table 5-6. Descriptive statistics showing the performance of CERES-Rice for treatments in 2009 that were not used to estimate cultivar parameters.

Variable	Data numbers	Obs	SD	Sim	SD	RMSE	NRMSE (%)	d-index	ME	r
PI date (DAP)	7	60.00	5.60	57.0	4.30	3.50	5.80	0.86	0.56	0.99
Anthesis date (DAP)	7	91.50	4.10	91.5	4.80	0.86	0.90	0.99	0.95	0.99
Maturity date (DAP)	7	123.00	4.10	123	6.01	1.80	1.40	0.96	0.79	0.99
LAI (cm^2cm^{-2})	25	1.89	0.77	1.19	0.91	0.97	51.0	0.62	-0.62	0.68
Tops weight (t ha^{-1})	25	4.80	3.40	4.80	3.70	1.10	23.0	0.97	0.89	0.95
SWC 0-15 cm (cm^3cm^{-3})	18	0.25	0.03	0.27	0.07	0.05	22.2	0.62	-3.3	0.76
SWC 15-30 cm^3cm^{-3})	18	0.31	0.03	0.27	0.05	0.05	16.0	0.65	-1.5	0.89
Grain yield (t ha^{-1})	7	4.16	1.50	3.92	1.80	0.70	17.8	0.95	0.75	0.93
Straw yield (t ha^{-1})	7	4.76	1.50	4.30	2.10	1.00	21.0	0.91	0.50	0.90
Tops N at maturity (kg ha^{-1})	7	75.7	26.4	81.2	38.0	18.4	24.3	0.90	0.44	0.89
Grain N at maturity (kg ha^{-1})	7	52.3	29.0	54.6	21.5	14.9	28.4	0.89	0.70	0.84

Sim - simulated; Obs- Observed; SD-Standard deviation; RMSE- Root mean square error; ME – Modeling efficiency; r- Spearman correlation coefficient; DAP- Days after planting.

Table 5-7. Descriptive statistics showing the performance of CERES-Rice when compared with independent data collected in the 2010 experiment.

Variable	Data numbers	Obs	SD	Sim	SD	RMSE	NRMSE (%)	d-index	ME	r
PI date (DAP)	8	61.00	4.30	58.00	3.20	3.16	5.20	0.79	0.38	1.00
Anthesis date (DAP)	8	92.60	3.60	93.50	3.70	0.93	1.00	0.98	0.92	0.99
Maturity date (DAP)	8	122.70	4.00	124.50	4.80	1.93	1.00	0.94	0.73	0.99
LAI (cm^2cm^{-2})	28	2.37	0.72	1.25	0.78	1.30	54.80	0.12	-2.30	0.59
Tops weight (t ha^{-1})	28	5.40	3.70	4.90	3.60	1.20	23.00	0.97	0.88	0.95
SWC 0-15 cm (cm^3cm^{-3})	18	0.31	0.03	0.27	0.06	0.05	16.90	0.58	-2.40	0.88
SWC 15-30 cm^3cm^{-3})	18	0.32	0.03	0.28	0.04	0.04	14.10	0.54	-1.92	0.91
Grain yield (t ha^{-1})	8	4.35	1.30	4.15	1.60	0.57	10.30	0.97	0.87	0.98
Straw yield (t ha^{-1})	8	5.29	1.30	4.20	1.60	1.20	22.30	0.80	0.06	0.96
Tops N at maturity (kg ha^{-1})	8	81.90	27.20	87.60	29.50	12.40	15.10	0.94	0.76	0.92
Grain N at maturity (kg ha^{-1})	8	52.60	19.40	56.40	23.40	6.60	12.50	0.97	0.87	0.98

Sim - simulated; Obs- Observed; SD-Standard deviation; RMSE- Root mean square error; ME – Modeling efficiency; r- Spearman correlation coefficient; DAP-Days after planting.

Table 5-8. Descriptive statistics showing the performance of CERES-Maize during the evaluation phase 2010-11.

Variable	Data numbers	Obs	SD	Sim	SD	RMSE	NRMSE (%)	d-index	ME	r
Anthesis date (DAP)	3	68.30	2.80	67.00	2.10	1.40	2.00	0.79	0.31	0.97
Maturity date (DAP)	3	118.30	3.50	119.00	4.90	1.15	9.00	0.95	0.76	0.96
Tops weight (t ha^{-1})	9	8.39	4.46	7.87	5.50	1.55	18.40	0.97	0.86	0.97
Grain yield (t ha^{-1})	3	6.23	0.32	6.02	0.20	0.23	3.60	0.71	0.24	0.99

Sim - simulated; Obs- Observed; SD-Standard deviation; RMSE- Root mean square error; ME – Modeling efficiency; r- Spearman correlation coefficient; DAP-Days after planting.

Table 5-9. Yield, water and N balance components in the rice seasonal analysis with CERES-Rice model.

Scenarios	Grain yield (t ha^{-1})	Water applied I+R (mm)	WP $_{I+R}$ (g grain kg^{-1} water)	Drainage (mm)	N Uptake (kg ha^{-1})	N leached (kg ha^{-1})	Mineralized N (kg ha^{-1})
AR-120 N -3 splits-60% ASW	6.27±0.65	893	0.70	227	142	40	53.5
AR-120 N -3 splits-80% ASW	5.58±0.55	1117	0.50	423	117	70	47.8
AR-120 N -3 splits-100% ASW	4.75±0.34	1407	0.34	681	93	98	40.8
AR-180 N -3 splits-60% ASW	7.24±0.51	888	0.81	222	176	45	72.2
AR-180 N -3 splits-80% ASW	6.79±0.50	1093	0.62	403	162	76	67.3
AR-180 N -3 splits-100% ASW	6.20±0.43	1376	0.45	656	137	106	55.4
AR-120 N -4 splits-60% ASW	6.52±0.51	904	0.72	238	147	39	54.7
AR-120 N -4 splits-80% ASW	5.92±0.44	1117	0.53	426	123	68	50.2
AR-120 N -4 splits-100% ASW	5.12±0.28	1405	0.36	685	98	94	44.3
AR-180 N -4 splits-60% ASW	7.52±0.40	891	0.84	224	184	42	76.5
AR-180 N -4 splits-80% ASW	7.23±0.39	1098	0.66	411	173	72	71.0
AR-180 N -4 splits-100% ASW	6.80±0.32	1384	0.49	668	151	100	59.5
FR-120 N -3 splits	6.11±0.17	1503	0.41	505	116	12	34.9
FR-180 N -3 splits	7.84±0.24	1519	0.52	518	166	12	45.9
AR- Potential production	7.96±0.38	-	-	-	-	-	-

AR- Aerobic rice; FR-Flooded rice; ASW- Available soil water; WP: Water Productivity.

Table 5-10. Yield, water applied, WP, and N uptake in the maize seasonal analysis with CERES-Maize model.

Scenarios	Grain yield (t ha^{-1})	Water applied I+R (mm)	WP (g grain kg^{-1} water)	N Uptake (kg ha^{-1})
N90-20% ASW	5.70±0.37	370	1.54	115
N90-30% ASW	6.18±0.38	401	1.54	116
N90-40% ASW	6.43±0.46	426	1.51	118
N90-50% ASW	6.45±0.47	451	1.43	119
N120-20% ASW	6.00±0.33	383	1.57	144
N120-30% ASW	6.63±0.41	416	1.59	146
N120-40% ASW	6.91±0.47	440	1.57	147
N120-50% ASW	6.94±0.47	461	1.50	148

ASW- Available soil water; WP: Water Productivity.

Table 5-11. Simulated average yield, water productivity of the aerobic and flooded rice-maize crop rotation.

Treatment	Grain yield (t ha^{-1})		WP (g grain kg^{-1} water)		Yield (t ha^{-1})	WP (g grain kg^{-1} water)
	Rice	Maize	Rice	Maize	Rice-maize system	
AR-120 N -M- 120 N	6.48±0.48	6.86±0.45	0.76	1.90	13.3	1.09
AR-120 N -M- 90 N	6.42±0.49	6.83±0.44	0.76	1.92	13.2	1.09
AR-180 N -M- 120 N	7.70±0.34	6.86±0.49	0.92	1.95	14.6	1.22
AR-180 N -M- 90 N	7.65±0.34	6.86±0.49	0.91	1.97	14.5	1.21
FR-120 N -M- 120 N	6.23±0.14	6.85±0.47	0.45	1.89	13.1	0.74
FR-120 N -M- 90 N	6.20±0.15	6.84±0.47	0.44	1.90	13.0	0.74
FR-180 N -M- 120 N	8.03±0.25	6.85±0.47	0.56	1.91	14.9	0.83
FR-180 N -M- 90 N	8.01±0.23	6.85±0.47	0.56	1.94	14.9	0.83

AR- Aerobic rice; FR-Flooded rice; WP: Water Productivity.

Table 5-12. Simulated water applied, drainage and seasonal ET of the aerobic and flooded rice-maize crop rotation.

Treatment	Water applied I+R (mm)		Drainage (mm)		ET (mm)	
	Rice	Maize	Rice	Maize	Rice	Maize
AR-120 N -M- 120 N	882±157	363±33	364±142	26±14	462±27	391±22
AR-120 N -M- 90 N	882±159	357±29	361±144	25±12	461±27	390±22
AR-180 N -M- 120 N	861±158	354±30	340±143	23±12	463±27	388±21
AR-180 N -M- 90 N	864±158	350±30	343±144	23±12	463+27	388±21
FR-120 N -M- 120 N	1405±91	365±33	505±10	18±12	455±27	393±22
FR-120 N -M- 90 N	1406±91	363±33	505±10	18±12	455±27	393±22
FR-180 N -M- 120 N	1429±93	361±33	522±10	20±14	461±23	389±21
FR-180 N -M- 90 N	1428±95	357±36	521±10	20±14	461±22	389±21

AR- Aerobic rice; FR-Flooded rice; ET- Evapotranspiration.

Table 5-13. Simulated average N balances in the aerobic and flooded rice-maize crop rotation.

Treatment	N uptake ($kg\ ha^{-1}$)		N leached ($kg\ ha^{-1}$)		N mineralized ($kg\ ha^{-1}$)		N denitrified ($kg\ ha^{-1}$)		N volatilized ($kg\ ha^{-1}$)	
	Rice	Maize	Rice	Maize	Rice	Maize	Rice	Maize	Rice	Maize
AR-120 N -M- 120 N	146±17	177±5	44.8±18	2.1±1	75±7	74±7	1.9±1	0.08±0.1	0.0±0.0	0.0±0
AR-120 N -M- 90 N	144±17	148±6	41.7±17	2.0±1	74±7	73±7	1.8±1	0.07±0.0	0.0±0.0	0.0±0
AR-180 N -M- 120 N	192±9	192±8	70.5±32	3.4±2	116±12	105±8	3.0±2	0.12±0.1	0.0±0.0	0.0±0
AR-180 N -M- 90 N	189±9	178±10	61.1±26	3.1±2	113±12	104±9	2.7±2	0.12±0.1	0.0±0.0	0.0±0
FR-120 N -M- 120 N	134±3	174±4	10.5±2	0.3±0.5	44±4	67±6	40.4±9	0.10±0.0	2.5±0.4	0.0±0
FR-120 N -M- 90 N	133±3	145±4	9.5±2	0.3±0.5	43±3	65±5	36.8±9	0.09±0.0	2.5±0.3	0.0±0
FR-180 N -M- 120 N	193±4	184±7	12.2±3	0.4±0.5	63±9	92±10	50.3±13	0.11±1.0	4.4±0.6	0.0±0
FR-180 N -M- 90 N	192±4	159±8	11.1±2	0.4±0.5	62±9	91±11	46.2±12	0.10±0.0	4.4±0.6	0.0±0

AR- Aerobic rice; FR-Flooded; M-Maize.

Table 5-14. Stability parameters of rice -maize crop rotation.

Cropping system	Yield ($t\ ha^{-1}$)	CV (%)	Rank	S_i^2	Rank	β_i	Rank	W_i^2	Rank	Over all
AR-120 N -M- 120 N	13.3	4.7	7	0.39	7	2.57	7	0.97	5	26
AR-120 N -M- 90 N	13.2	4.9	8	0.42	8	2.88	8	0.96	6	30
AR-180 N -M- 120 N	14.6	4.2	6	0.37	6	1.13	1	1.06	3	16
AR-180 N -M- 90 N	14.5	4.2	5	0.37	5	1.15	2	1.05	4	16
FR-120 N -M- 120 N	13.1	3.9	3	0.26	1	2.25	4	0.95	7	15
FR-120 N -M- 90 N	13.0	3.9	4	0.26	2	2.23	3	0.95	8	17
FR-180 N -M- 120 N	14.9	3.8	2	0.31	4	2.38	5	1.08	1	12
FR-180 N -M- 90 N	14.9	3.7	1	0.31	3	2.43	6	1.08	2	12

CV- Coefficient of variation; S_i^2-Variance across environments; Bi-Regression coefficient; W_i^2- Ecovalance parameter; AR-Aerobic rice; FR-Flooded rice; M-Maize.

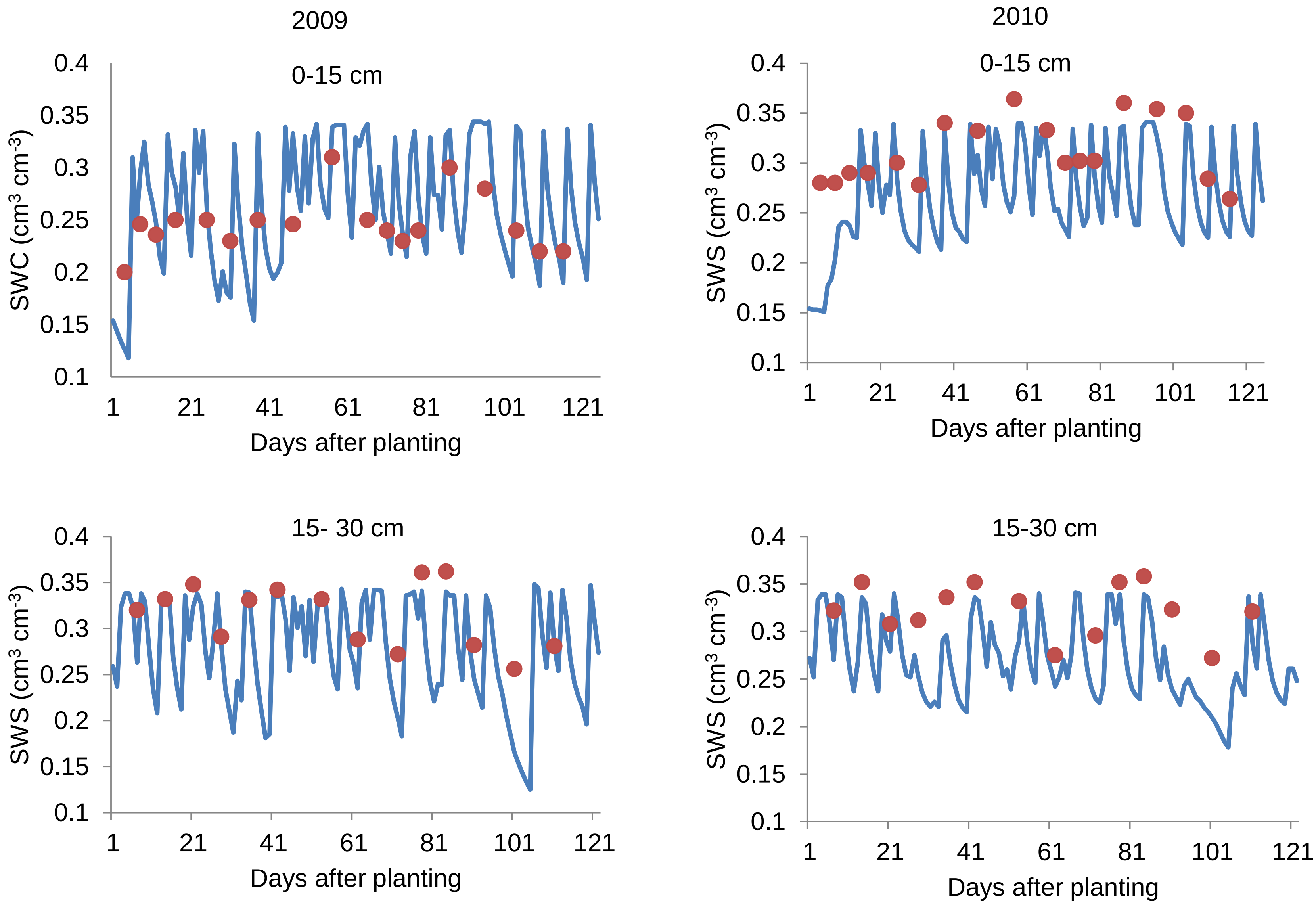
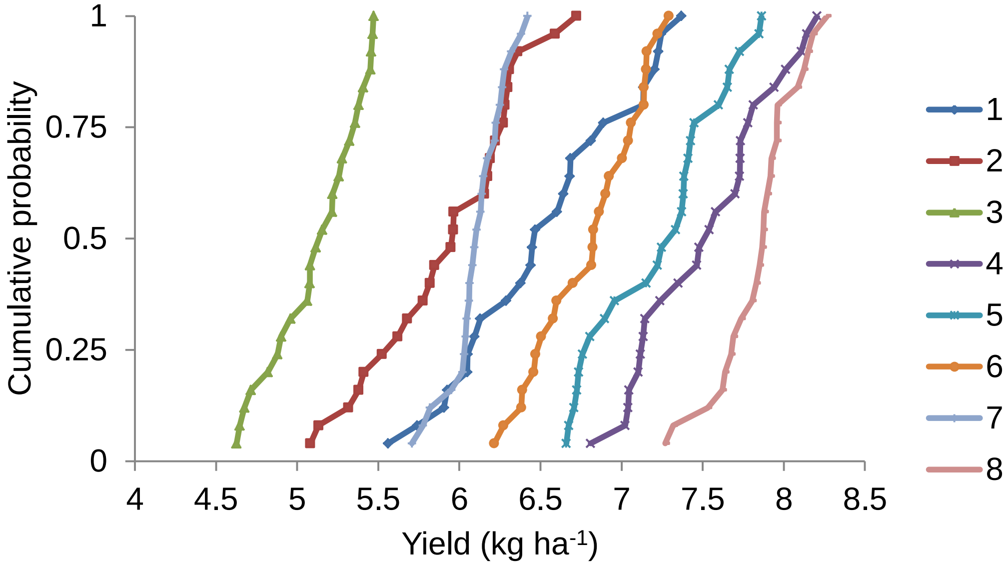


Figure 5-1. Simulated (lines) and measured (points) volumetric soil water content (SWS) during 2009 and 2010, in days after planting in aerobic rice.

(a)



1= AR 120N-60% ASW; 2= AR 120N-80% ASW; 3= AR 120N-100% ASW; 4= AR 180N-60% ASW; 5= AR 180N-80% ASW; 6= AR 180N-100% ASW; 7= FR 120N; 8= FR 180N

(b)

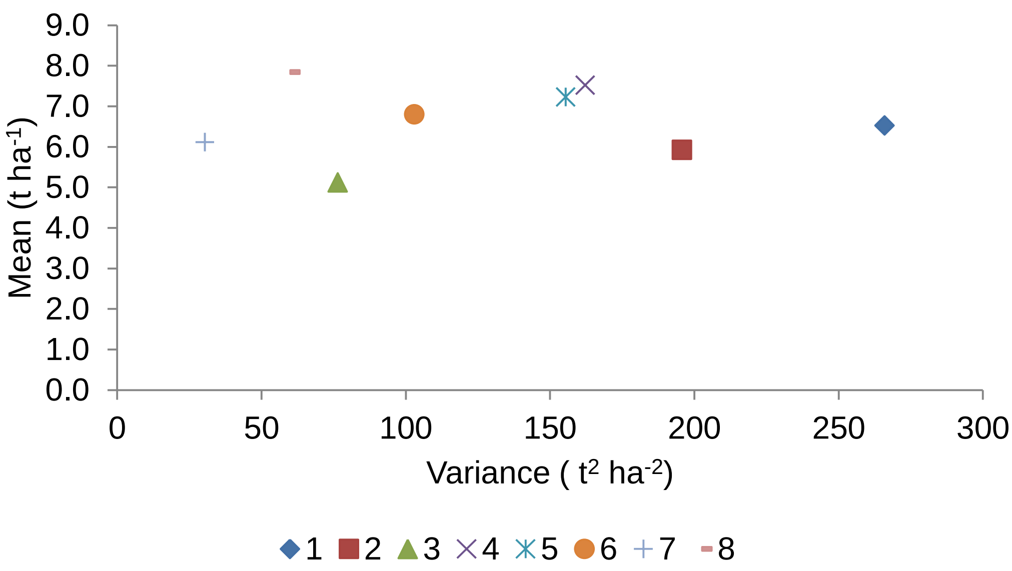


Figure 5-2. Cumulative probability function and mean-variance (E-V) plots for different treatment scenarios of rice.

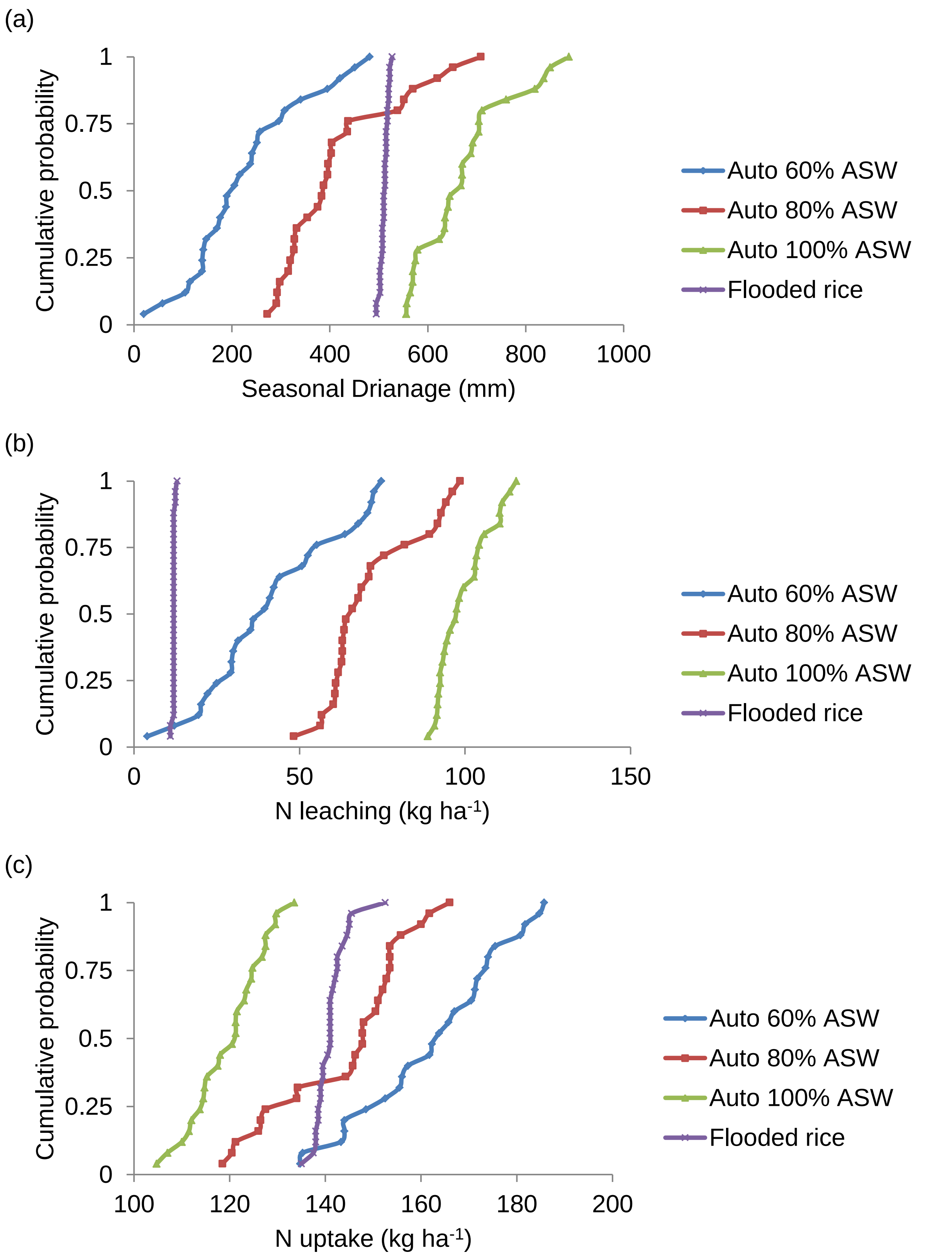
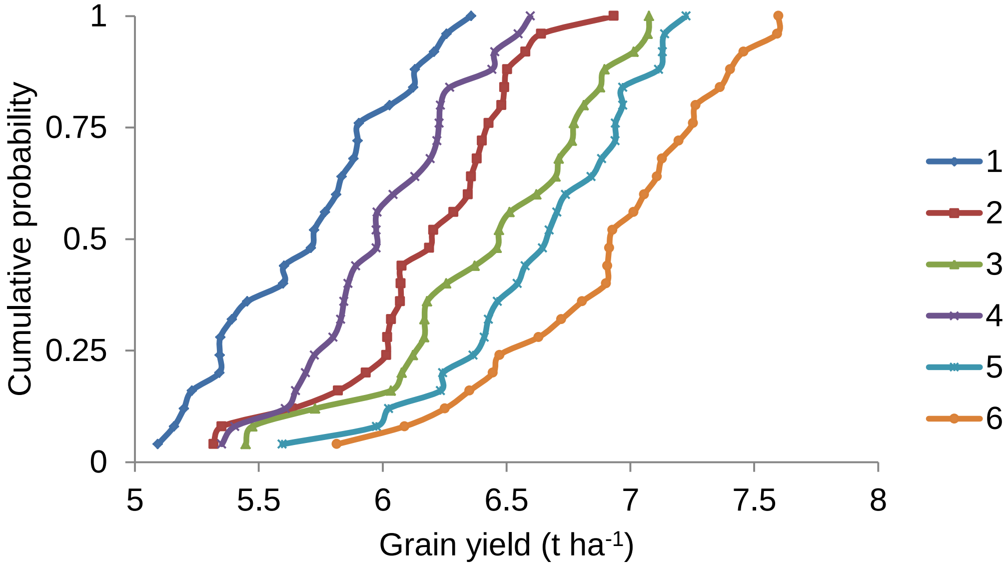


Figure 5-3. Cumulative probability function plots of seasonal drainage, N uptake and N leaching for irrigation scenarios in aerobic and flooded rice.

(a)



1= MZ 90 N-20% ASW 2= MZ 90 N -30% ASW
3= MZ 90 N -40% ASW 4= MZ 120 N -20% ASW
5= MZ 120 N -30% ASW 6= MZ 120 N -40% ASW

(b)

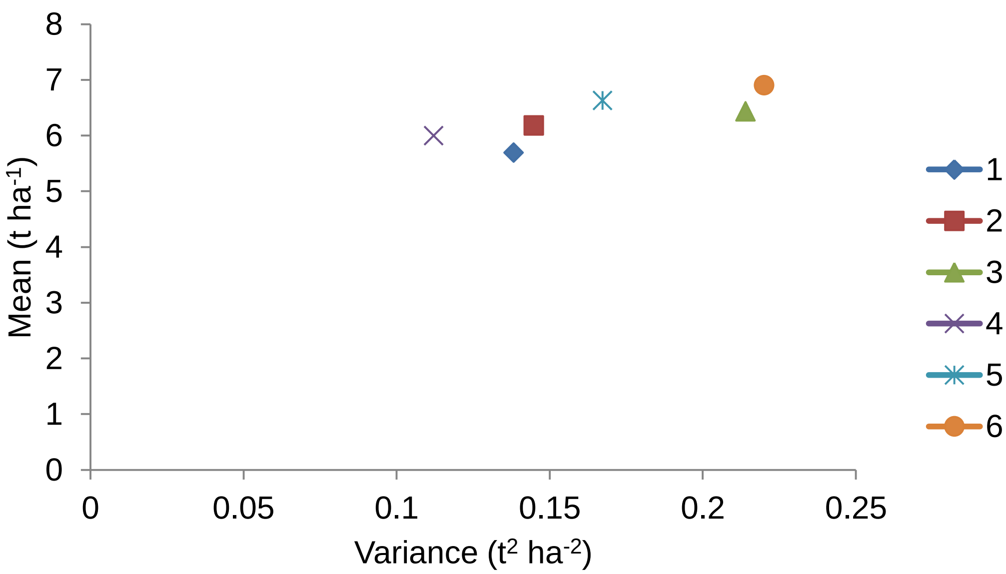


Figure 5-4. Cumulative probability function and mean-variance (E-V) plots for different treatment scenarios of maize.

CHAPTER 6
STUDY OF SPATIAL WATER REQUIREMENTS OF RICE UNDER VARIOUS CROP ESTABLISHMENT METHODS USING GIS AND CROP MODELS.

Background

Traditional rice transplanting method of cultivation faces severe yield limitations due to frequent monsoon rain failures, which results in water stress during critical periods of rice growth. To meet the water demands of traditional flooded rice, farmers need to pump water from the underground aquifers. This continuous pumping causes drying up of the underground water and creates serious ecological and environmental consequences. Conjunctive use of rainfall and irrigation can conserve precious underground water and increase the overall water productivity of irrigation schemes. Developing efficient irrigation scheduling procedures for rice can save water by minimizing the various losses and can enable to irrigate more area with the available water resources. Rice growth and development depends up on the complex interactions between variety, soil, climatic and management factors all of which vary both in space and time (Rao and Rees, 1992). Development of efficient irrigation management packages requires careful monitoring of these factors continuously along with associated effects on crop growth and development.

Crop simulation models are valuable tools for evaluating potential effects of environmental, biological and management factors on crop growth and developments. These tools are handy in these situations and provide practical means for scheduling irrigations. Crop models were evaluated and used for many soil and environmental conditions across the world. In the past, these models have been successfully utilized in yield predictions (Jagtap and Jones, 2002), irrigation planning for crops (Behera and Panda, 2009), optimization of irrigation water use (Fortes et al., 2005; Bulatewicz et al., 2009), comparison of various scenarios and strategies (Rinaldi, 2004; Rinaldi et al., 2007), analysis of yield trends over time (Liu et al., 2011) and many more. These models are generally point-based systems as they mostly use site specific parameters such as weather, physical and chemical parameters of soil, water management, agronomic practices and the output simulation results can only be the representative of a small field. However, these models need to be applied at larger scales in order to be economically useful so that the effects of various alternate management strategies across the watershed or the region could be analyzed. Studies conducted in various parts of the world on linking crop models with a Geographical Information System (GIS) have demonstrated a strong feasibility of crop modeling applications at a spatial scale (Engel et al., 1997; Thornton et al., 1997; Heinemann et al., 2001). GIS is capable of using spatial data and can be very handy in environmental and agricultural modeling (Hartkamp et al., 1999; Beinroth et al., 1998). Several researchers successfully utilized crop models that are part of Decision Support System for Agro Technology Transfer (DSSAT) and GIS in studying spatial water requirement of crops, yield forecast and climate change impacts at watershed and regional scales (Hansen et al., 1998).

The main objective of present study was to investigate the spatial variations in the simulated yield, water balance and nitrogen (N) leaching from different rice cultivation scenarios in a semi-arid sub watershed in southern India. The calibrated and evaluated DSSAT CERES-Rice model was used to predict yield variations due to soil types and three rice establishment methods. The output results on yields, water applied, drainage and N leaching were spatially mapped in the entire watershed using Arc GIS Thiessen polygon method.

Materials and Methods

Description of Study Area

The Wargal village of Wargal mandal (an administrative unit containing 15-20 villages) is located at a latitude of 17^0 41’19.4’’ N and a longitude of 78^0 29’24.0’’ E, with an elevation of 590 m above sea level in Medak district of Andhra Pradesh, India. The total geographical area of Wargal village is 2618 ha with 2522 ha of cultivable land, of which 405 ha are under irrigation by tanks and bore wells. The soils of the village are mostly red chalka (Red sandy/sandy clay loams – Alfisols, 2336 ha) and black cotton soils (Vertisols, 280 ha). The Kothakunta sub watershed in Wargal village with an area of 512 ha was selected for the study (Figure 6-1).The watershed mostly consists of red soils. The physiography of the area is undulating having a slope of 1-5%, slightly eroded, and moderately drained. The annual average rainfall in the watershed is 780 mm; about 80% of which is received during June-September from the southwest monsoon. Rice is the major crop grown in the area which is transplanted during July, after the onset of monsoon, and is harvested in November.

The CERES- Rice Model

The CERES-Rice model simulates crop growth and development on daily time step. Water balance component of the model calculates infiltration, runoff, drainage and evapotranspiration to assess the soil water balance. This is a one-dimensional model and computes the daily changes in soil water content in a soil layer due to infiltration, irrigation, vertical drainage, unsaturated flow, soil evaporation, plant transpiration and root water uptake (Ritchie, 1998). Infiltration is calculated based on difference between rainfall or irrigation and runoff. Drainage is assumed constant over entire day and computed for each layer using the drained upper limit and lower limit values of soil water content. When the water content in each layer is above the drained upper limit, water drains to next layer. The amount of water passing to each layer is then compared to statured hydraulic conductivity (K_{sat}) of that layer. If the K_{sat} is less than the drainage then the actual drainage is limited to the K_{sat} value. The model uses the Priestly–Taylor method to estimate daily potential evapotranspiration. The CERES- Rice model also simulates flood water depth, flood water evapotranspiration and runoff, only if the flood water depth exceeds bund height. The model also simulates the temporal changes in bulk density and saturated hydraulic conductivity due to puddling.

Soil Data

Soil samples were collected from 34 locations across the watershed area at two to five depth classes (1 meter maximum) at each point. Soil physico-chemical properties such as texture, hydraulic parameters, bulk density, organic matter, available N, phosphorus and potassium were determined for each sample. Additional soil parameters, including the soil albedo, drainage constant, and runoff curve number were also estimated based on the soil texture data from the generic soil database available in the DSSAT-models (Tsuji et al., 1998).The 34 soil reference points were converted into polygons using the Thiessen method which is one of the simplest method of interpolation by drawing boundaries according to the distribution of soil sample points using ArcGIS v10.0 software (Environmental Systems Research Institute, 2011).Later the converted polygons were clipped with soil and rice crop area maps (Figure 6-2).

Weather Data

Daily weather data of the area from 1975 to 2009 was obtained from the International Crop Research Institute for Semi-Arid Tropics (ICRISAT), Hyderabad. The weather parameters included daily solar radiation (MJ $m^{-2}day^{-1}$), maximum and minimum air temperatures (^oC), and rainfall (mm day^{-1}).

Crop Management Inputs

Crop management data used for three simulations were presented in the Table 6-1. All the treatments received 180 kg N ha^{-1} applied in three equal splits, each one at the time of planting, maximum tillering and at panicle initiation stage. In the rainfed and flooded rice treatments, crop was planted initially in the nursery and 30-day old seedlings were transplanted in the main field. In aerobic rice treatment, seeds were planted at rate of 300 seeds m^{-2} in 22.5 cm rows apart.

Initial Conditions

The initial conditions on soil water, nitrate N and ammoniacal N were the actual values estimated during the data collection for 34 soil sample. An estimate of the above and below ground residues from the previous crop also recorded and provided as an input for the model.

Model Calibration and Management Options Simulated

The most commonly grown short duration, high yielding rice variety in Wargal study area was used for the simulations (MTU 1010). The CERES-Rice genetic coefficients for MTU 1010 variety were estimated with GLUE method with independent field experiment data obtained in 2009 and 2010 under similar soil and climatic conditions. The model was simulated for the following three scenarios

1. Puddled flooded rice receiving 180 kg N ha^{-1} grown under rainfed conditions (RR).
2. Puddled flooded rice receiving 180 kg N ha^{-1} rice grown under irrigated conditions maintaining 2 cm depth of water from transplanting to flowering and 5 depth of water from flowering to one week before maturity (FR).

3. Aerobic rice with 180 kg N ha^{-1} and automatic irrigation with 40 mm, when soil available water (ASW) in top 30 cm equals to 60% (AR)

The basis for using 40 mm irrigation at 60% ASW was due to the fact that this treatment was found optimum for attaining the highest yields of aerobic rice under similar climatic conditions using the MTU 1010 variety. The output results on grain yield, seasonal evapotranspiration (ET), seasonal drainage, irrigation volumes and N balance components such as crop uptake, N leaching were mapped to visualize their spatial and temporal variability under three different scenarios. Total annual underground irrigation withdrawals, water pumping hours, runoff, and N leaching in each polygon were also calculated and summed to obtain the totals for the entire watershed under the three scenarios. Water productivity (g grain kg^{-1} of water) and irrigation water use efficiency (g grain kg^{-1} of water) were also calculated for each scenario. Annual irrigation withdrawals for each scenario were estimated as.

$$IR_W = \sum_{i=1}^{n} X_i IR_i \tag{6-1}$$

Where IR_w is the annual irrigation withdrawals from the entire rice area of the watershed, X is the area of the each polygon and IR is the irrigation amount applied to rice crop grown in that particular polygon. Similar procedure was followed for calculating annual drainage and N leaching in the watershed.

Water productivity (WP, g grain kg^{-1} of water) and irrigation water use efficiency (IWUE, g grain kg^{-1} of water) can be estimated as.

$$WP = \frac{Y}{WA_{(I+R)}} \tag{6-2}$$

$$IWUE = \frac{Y - Y_R}{IR} \tag{6-3}$$

Where Y represents the rice grain yield, WA is the total water applied, includes irrigation (I) and rainfall (R), Y_R is the yield obtained under rainfed conditions, IR amount of irrigation water applied during crop growth.

Results and Discussion

Yield

The yields simulated by the model under rainfed conditions were fairly consistent with the typical range of yields reported for the area. Simulated rice yields varied with the soil type and were higher in sandy clay loam soil than in the sandy loam soil. Rainfed conditions resulted in lower yields with an overall mean of 5954 kg ha^{-1} (Table 6-2), ranging from 2746 kg ha^{-1} to 7217 kg ha^{-1}.This indicates that crop yields varied greatly among the polygons across the region even though the weather is normally assumed to be uniform across the watershed area. The simulated yields under flooded and aerobic conditions were more than the general yields previously reported in the area and ranged between 7147 – 8659 kg ha^{-1} and 6753- 8351 kg ha^{-1} respectively. The yields under aerobic and flooded rice were 22% and 27% higher than the rainfed rice. Higher yields were simulated in western and central part of the watershed under both flooded and rainfed conditions while under aerobic rice, the central and eastern parts showed higher rice yields.

Water Balance Components

Information on water balance components is important to understand contribution of irrigation to the yields and various losses. Various water balance components such as irrigation volume, ET, drainage, runoff and soil water available after crop harvest were studied under flooded, rainfed and aerobic rice scenarios. In flooded rice scenario, the maximum amount of irrigation water applied was 917 mm compared to 393 mm in the aerobic rice suggesting that substantial amount of water could be saved under the aerobic system (Table 6-3). The seasonal irrigation volumes in flooded system ranged from 747 to 917 mm averaged across the locations compared to 187-393 mm under the aerobic rice. Increased irrigation volumes under flooded system resulted in increased runoff as wells as increased drainage. In the aerobic system, the average amount of irrigation applied across the watershed was 53% of ET, while it was 198% of ET the flooded rice. The seasonal drainage volumes in flooded rice were considerably high and ranged from 517 mm to 536 mm. This was one of the reasons for higher water requirement of rice under this system. The drainage volumes under aerobic system, on the other hand, were lower (119 mm to 410 mm) as there was no standing water maintained in the field throughout the crop growth. Water productivity was calculated based on the simulated yield and total volume of water (I +R) for rainfed, aerobic and flooded rice. The results showed that among the three scenarios, the rainfed rice system showed the highest WP (0.38 – 1.03 g grain kg^{-1} of water applied) followed by the aerobic rice (0.63 – 0.82), and the flooded rice (0.52-0.62). The IWUE decreased with increased irrigation applications. Adoption of aerobic rice cultivation resulted in an average IWUE of 0.5 g grain kg^{-1} of water applied with a standard deviation of 0.26 across the study area compared to the 0.19 g grain kg^{-1} of water applied with a standard deviation of 0.1 with flooded rice. The spatial distribution of water balance components in the three scenarios are presented in the Figures 6-4, 6-6 and 6-8.

Nitrogen Leaching

Among the irrigation scenarios studied, aerobic rice was associated with the greatest amount of N leaching. The simulated N leaching amounts varied considerably among different soil types across the study area with ranges of 8- 47 kg ha^{-1}, 6-15 kg ha^{-1} and 0.6-13 kg ha^{-1} under aerobic, flooded and rainfed scenarios, respectively. The spatial distribution of leaching in aerobic rice was found to be similar to the spatial distribution of drainage.

Watershed Level

Irrigation Withdrawals

The mean seasonal irrigation withdrawals for the entire watershed under flooded and aerobic rice scenarios were 31.7 x 10^5 m^3 and 8.7 x 10^5 m^3, respectively. It was found that in order to meet the increased irrigation demand under flooded system, irrigation pumping hours needed to be increased to 3.7 times than the pumping hours under aerobic system (Table 6-4). The spatial distribution of irrigation withdrawals and pumping are presented in the Figures 6-3, 6-5 and 6-7.

Deep Drainage

The maximum amount of simulated drainage was 19.1 x 10^5 m^3 under flood irrigation scenario. In flood irrigation scenario, 60% of pumped irrigation water resulted in drainage while it was 120% under the aerobic rice suggesting that most of the rainfall directly contributes to drainage under aerobic system. The results also indicate that most of the water pumped in expense of electrical energy was lost through drainage rather than being utilized by the crop.

Nitrate Leaching

Maximum amount of N leached was 7.54 t per season under aerobic rice, while the minimum amount N leached was 1.34 t per season under rainfed conditions. The lower leaching losses in flooded and rainfed rice were possibly because of the anaerobic growing conditions which normally result in reduced soil conditions as opposed to the aerobic rice where highly oxidized condition is likely to enhance nitrate leaching (Belder et al., 2005; Zhang et al., 2009).

Conclusions

The present study on spatial and temporal water requirement of alternate rice irrigation management scenarios demonstrated the capability of DSSAT models coupled with GIS in presenting the spatial patterns of simulated results. Developing thematic maps on N and water balances at watershed or region level will make these models a useful tool for supporting policy making in integrated water resources management. In the study it was observed that irrigation played a crucial role in improving the rice yields and WP. The simulation results also indicate that IWUE is 50% higher in aerobic rice compared to rainfed rice. Higher water productivity and water savings are possible in rice cultivation by following aerobic rice method. The water balance studies indicates that in flooded rice, 63% of the total water applied (I+R) was from irrigation and the losses through deep percolation and runoff accounted for 53% of the total water applied. While, in aerobic rice only 27% of the total water applied was from irrigation with 45% of applied water lost through runoff and deep percolation. These type of studies up to watershed scales are very useful in decision making as most of the data presently available in countries like India were up to district level only. Further, there are many assumption and uncertainties in this study especially DSSAT one dimensional water balance model and simulating the crop yields based on single weather station data for entire watershed. Besides these there are other factors like weeds, pest and diseases that can influence crop yields especially under aerobic rice system which was not considered in the present study. Despite these limitations the integration of crop models with GIS can assists the researchers and policy makers in studying the overall water productivity up to the regional or watershed scales.

Table 6-1. Crop management information.

Scenario	Planting date	Plant population m^{-2}	Row spacing
Rainfed rice (RR)	5 August	33	30 cm
Flooded rice (FR)	5 August	33	30 cm
Aerobic rice (AR)	5 July	150	22.5 cm

Table 6-2. Average and standard deviation of rice yields, water productivity and irrigation use efficiency under different crop establishment method as simulated by CERES-Rice model in the watershed.

Treatment	Water applied I+R (mm)	No. of pumping hours	Yield (kg ha^{-1})	WP (g grain kg^{-1} of water)	IWUE (g grain kg^{-1} of water)
Rainfed rice	699±5	-	5954±783	0.85±0.12	-
Flooded rice	1356±31	299±11	7572±349	0.56±0.02	0.19±0.10
Aerobic rice	948±51	88±18	7271±301	0.77±0.03	0.50±0.26
ANOVA					
Treatments		***	***	***	***

Pumping hours calculated based on normal discharge of 8 lps for a 5HPmotor.
WP-Water productivity; IWUE- Irrigation water use efficiency.
* $P< 0.05$; ** $P<0.01$; *** $P<0.001$; NS= non-significant ($p>0.05$).

Table 6-3. Average and standard deviation of water balance components of rice as influenced by different crop establishment methods as simulated by CERES-Rice model in the watershed.

Method	Irrigation volume (mm)	Seasonal ET (mm)	Drainage (mm)	Runoff (mm)	Soil water available after harvest (mm)
Rainfed rice	-	514±24	85±10	97±23	39±11
Flooded rice	861±30	434±4	522±5	193±1	164±34
Aerobic rice	253±53	478±10	289±56	137±67	79±17

ET- Evapotranspiration.

Table 6-4. Averages and standard deviations for 35 years of simulations for total rice production, irrigation amount, deep drainage, pumping hours, and N leaching for different rice crop establishment scenarios.

Method	Production (1X 10^3 t)	Irrigation (1 X 10^5 m^3)	Deep drainage (1 X 10^5 m^3)	Pumping hours (1 X 10^4 hr.)	N leaching (t $season^{-1}$)
Rainfed rice	2.21 ±0.76	-	3.0±2.9	-	1.34±0.9
Flooded rice	2.78±0.10	31.7±3.0	19.1±0.6	10.9±1.0	5.21±0.19
Aerobic rice	2.65±0.10	8.70±1.4	10.5±2.3	2.98±0.5	7.54±2.6

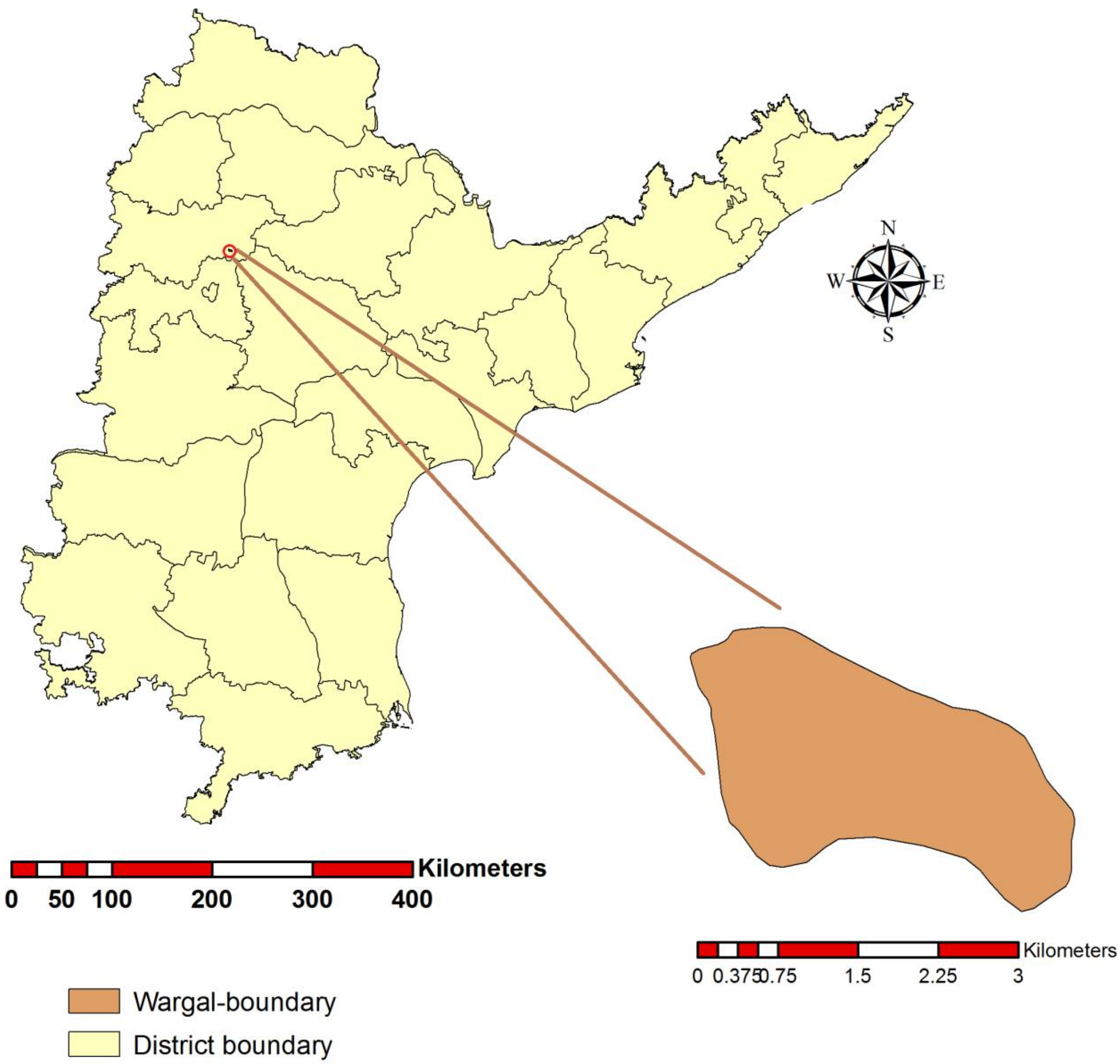


Figure 6-1. Location of study area- Kothakunta sub watershed, Wargal, Medak District, A.P, India.

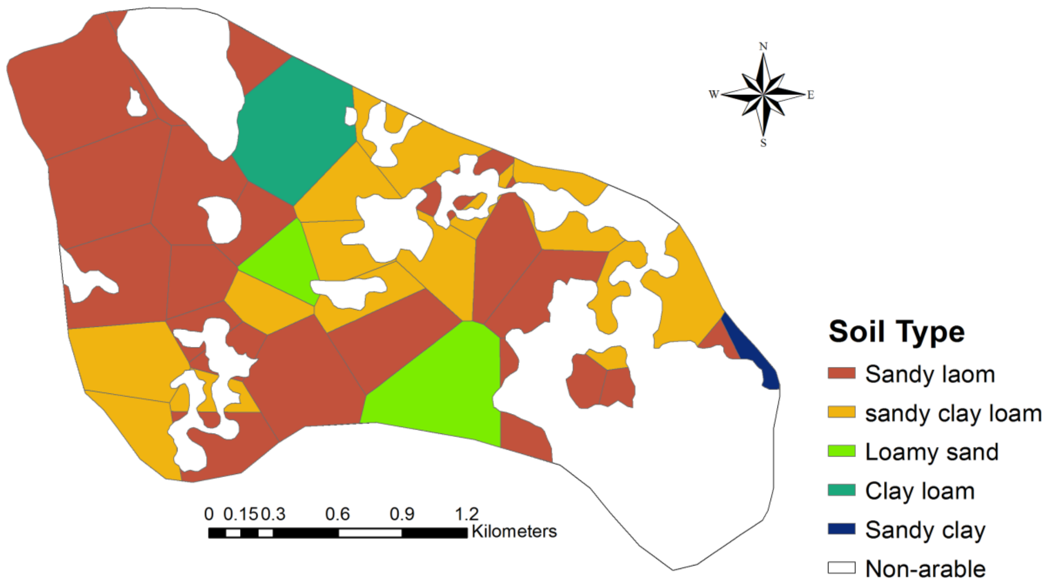


Figure 6-2. Distribution of main soil types in Kothakunta sub watershed, Wargal, Medak District, A.P, India.

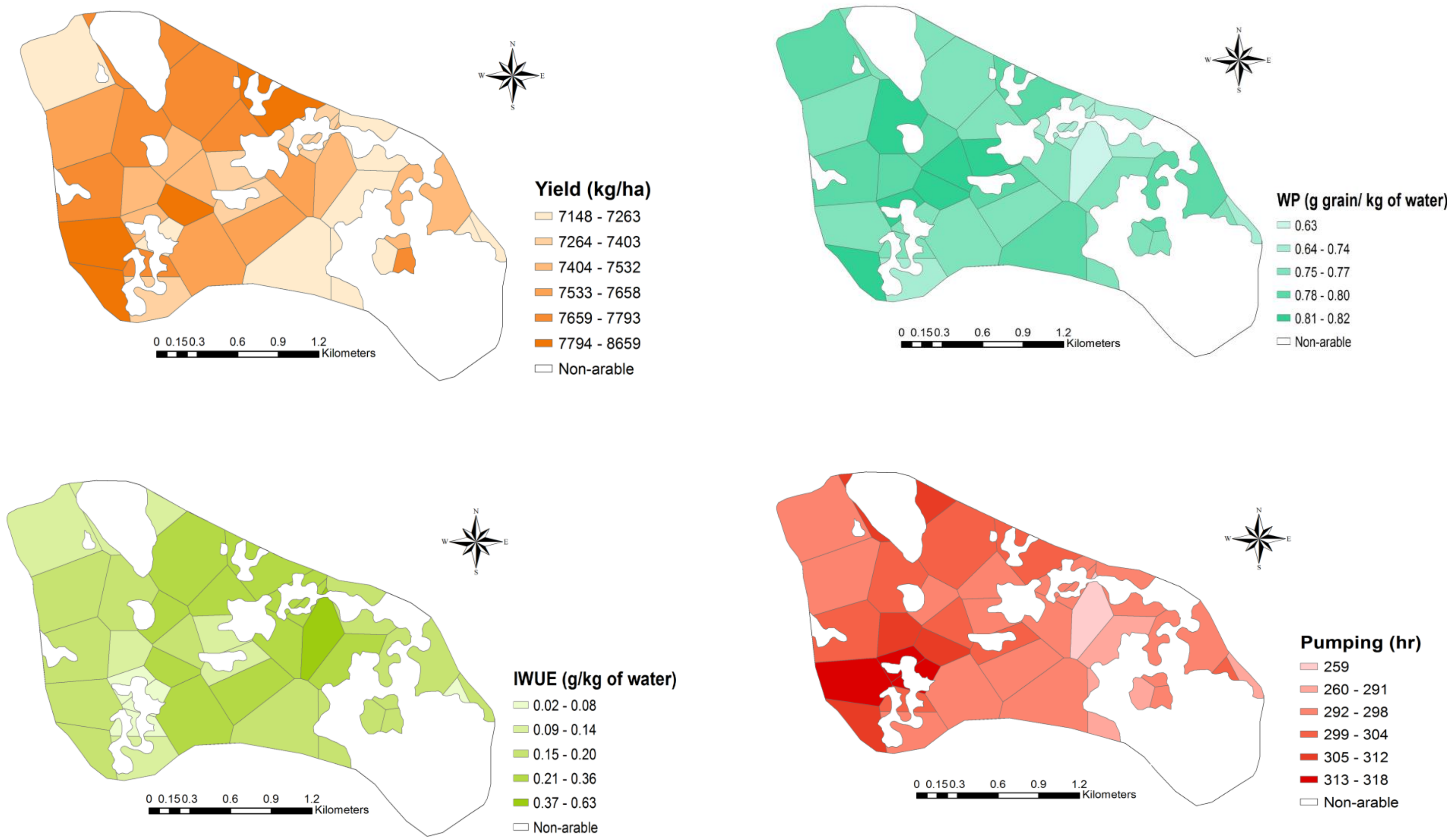


Figure 6-3. Yield, WP, IWUE simulated by the CERES-Rice model and pumping hours under flooded rice scenario and mapped for the 34 soil polygons.

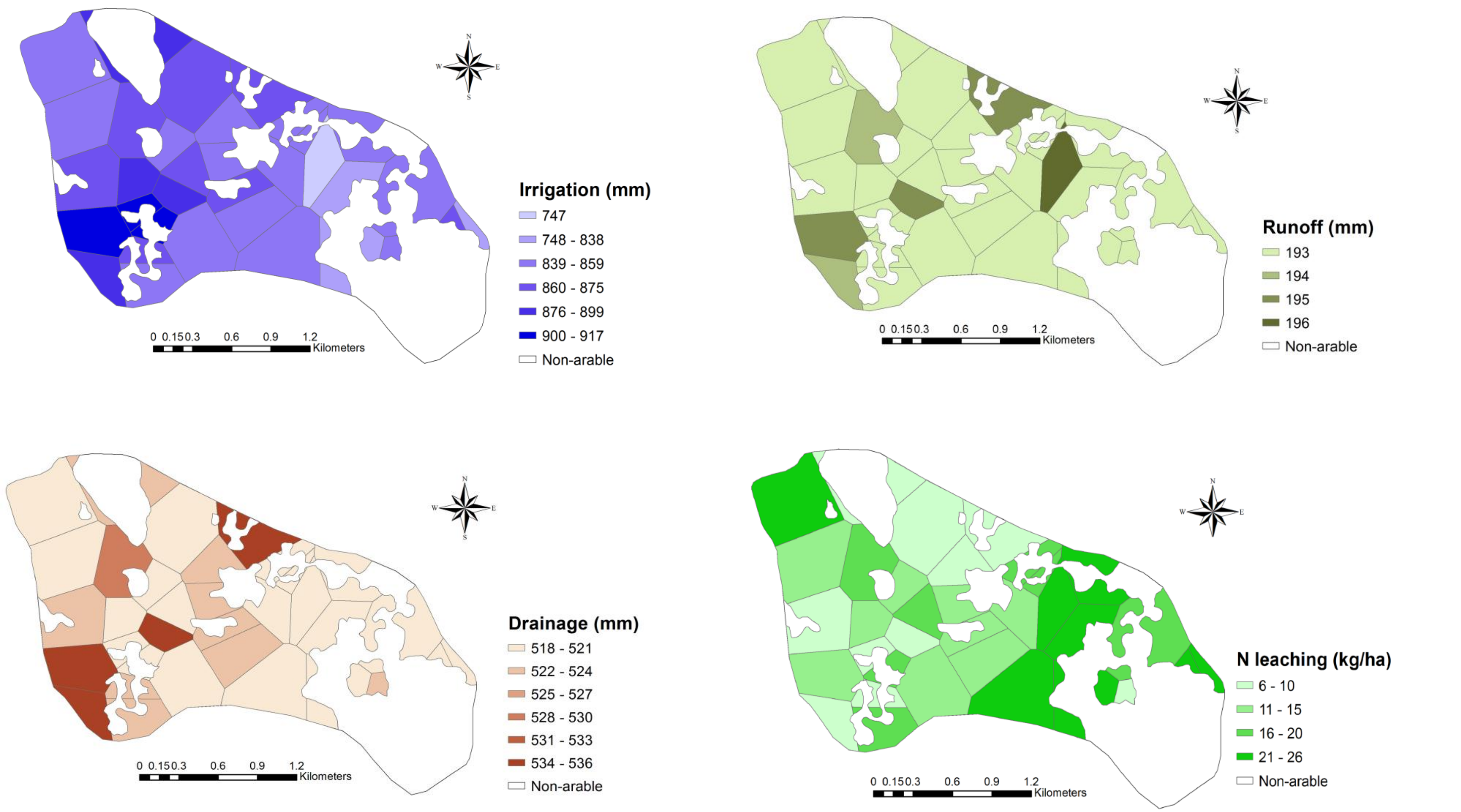


Figure 6-4. Irrigation water, runoff, seasonal drainage and N leaching simulated by the CERES-Rice model under flooded rice scenario and mapped for the 34 soil polygons.

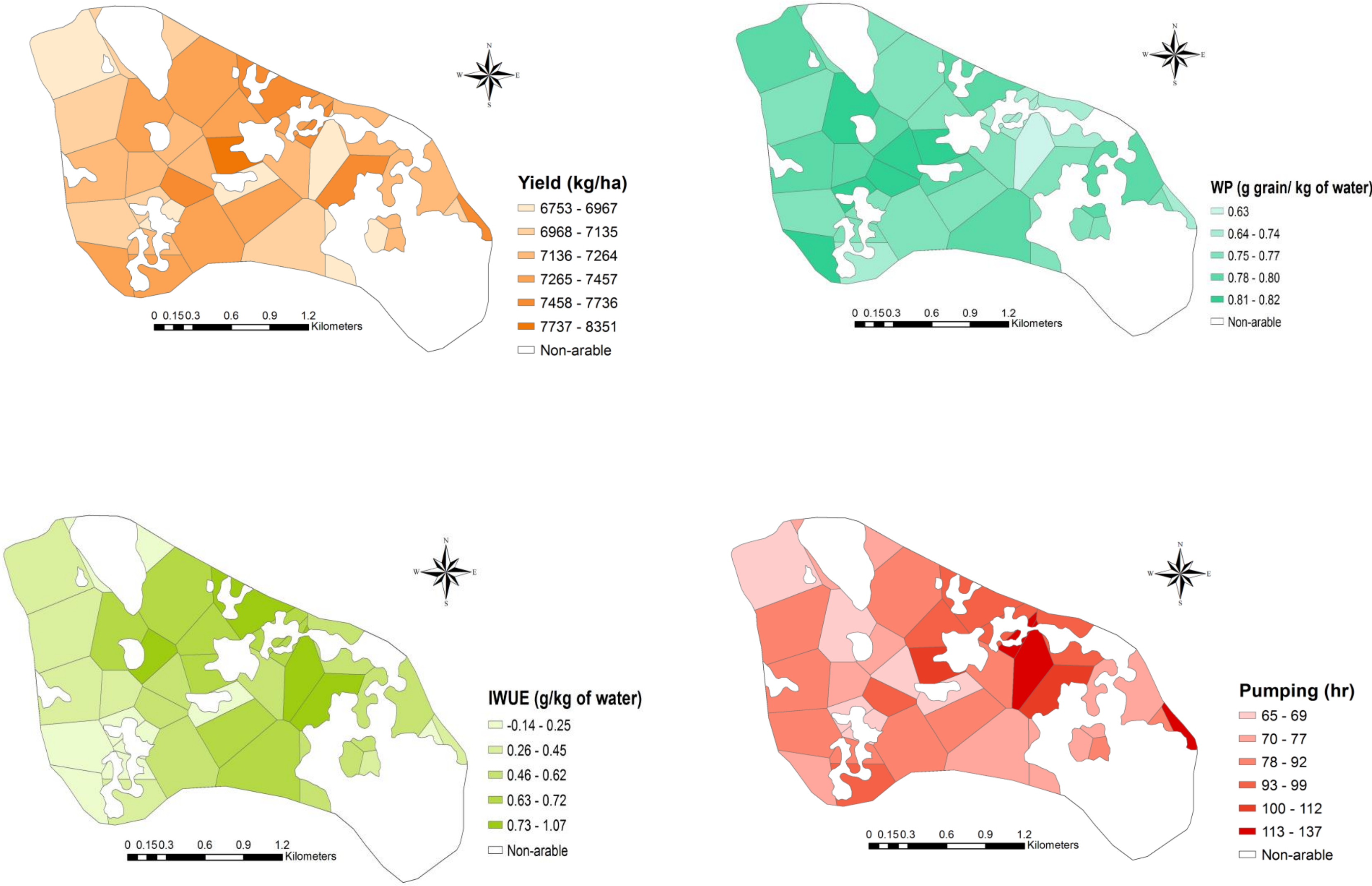


Figure 6-5. Yield, WP, IWUE simulated by the CERES-Rice model and pumping hours under aerobic rice scenario and mapped for the 34 soil polygons.

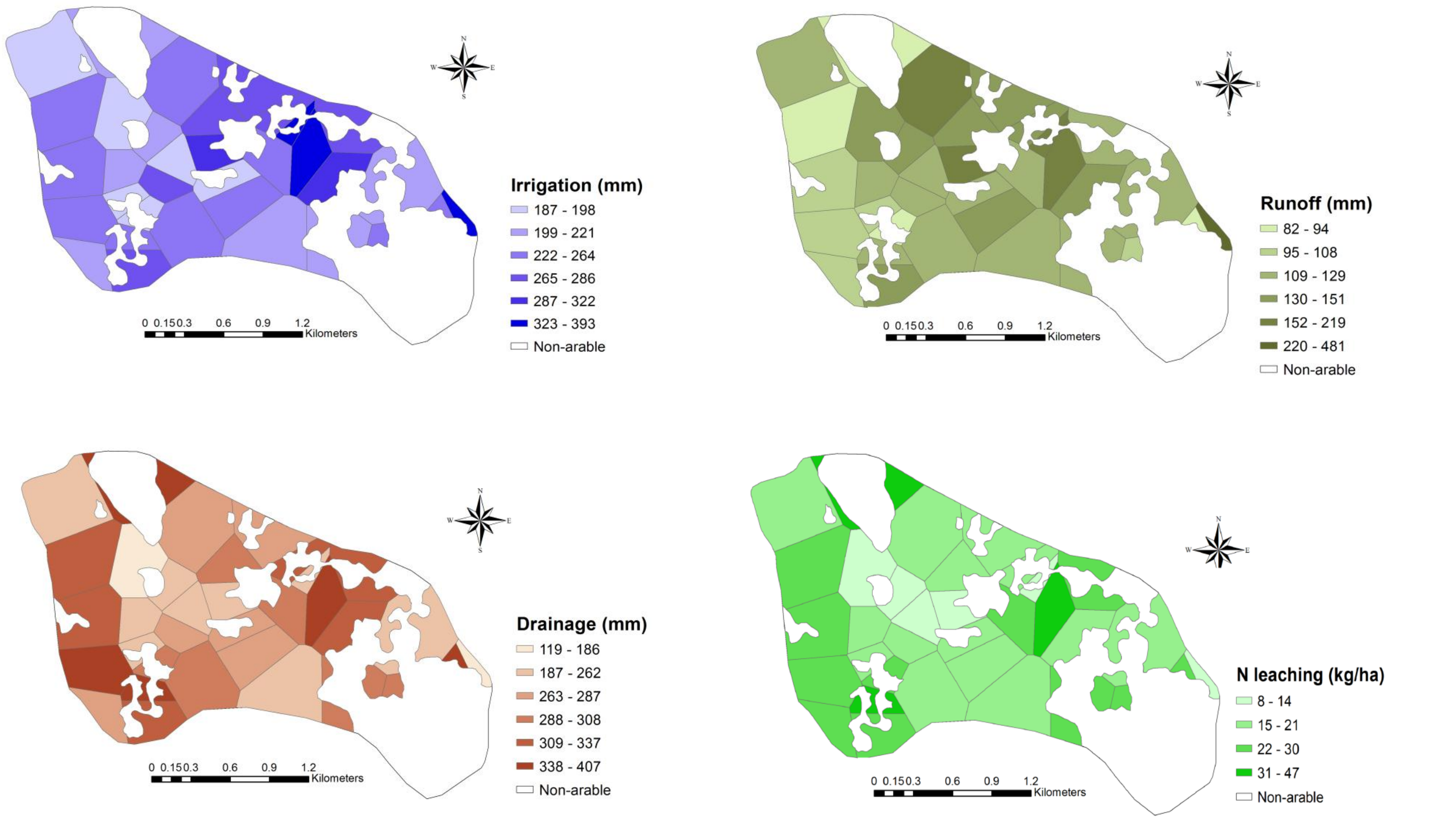


Figure 6-6. Irrigation water, runoff, seasonal drainage and N leaching simulated by the CERES-Rice model under aerobic rice scenario and mapped for the 34 soil polygons.

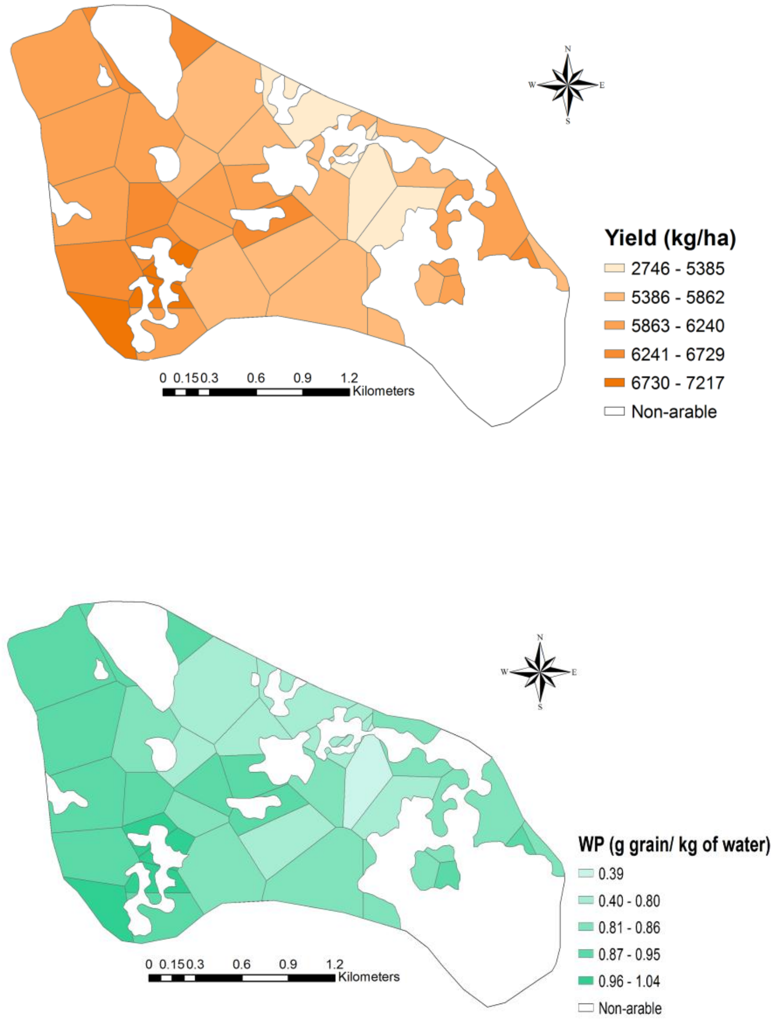


Figure 6-7. Yield and WP simulated by the CERES-Rice model under rainfed rice scenario and mapped for the 34 soil polygons.

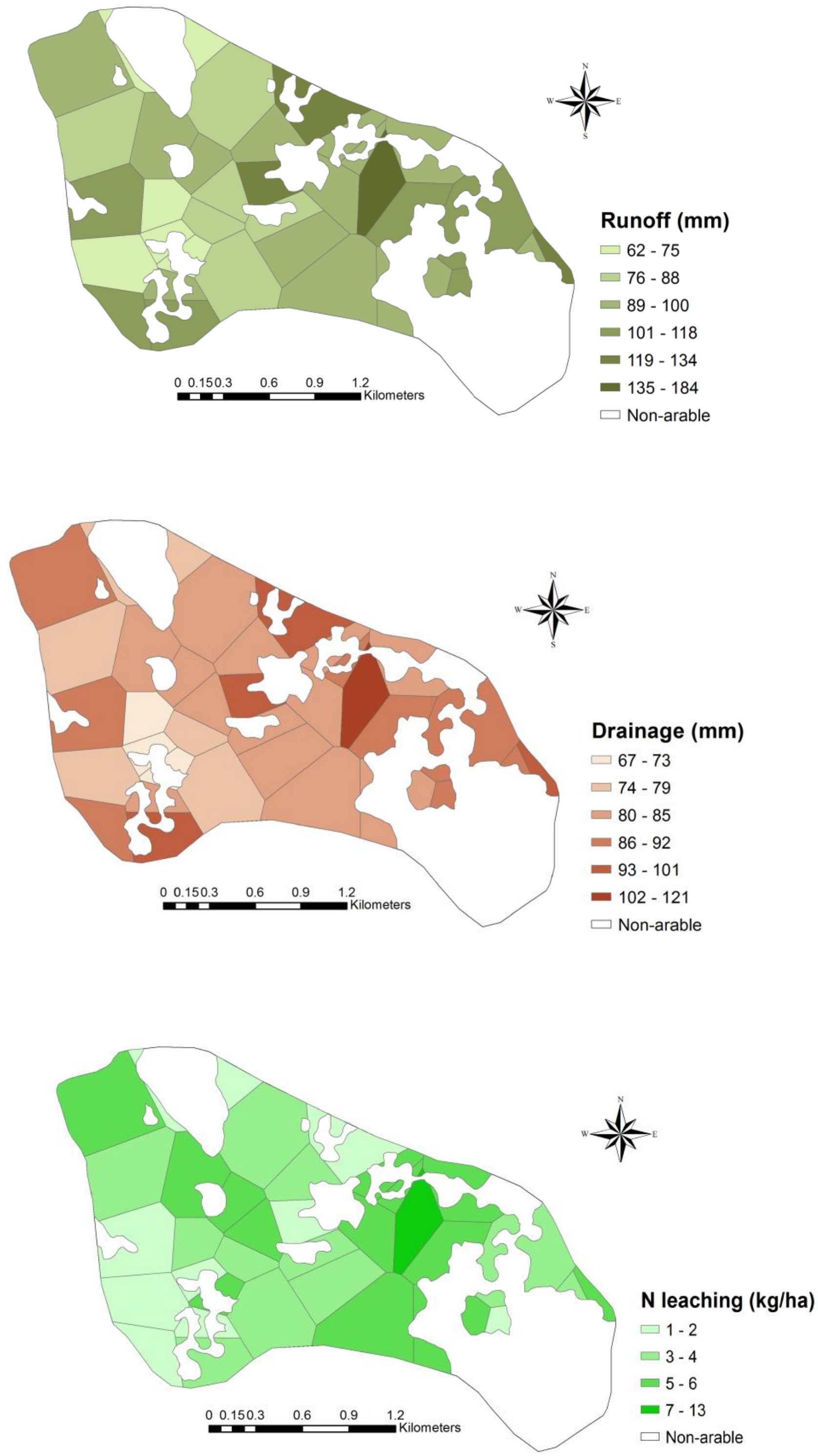


Figure 6-8. Runoff, seasonal drainage and N leaching simulated by the CERES-Rice model under rainfed rice scenario and mapped for the 34 soil polygons.

CHAPTER 7
CONCLUSIONS

The response of rice-maize (R-M) cropping system under two methods of crop establishment (flooded and aerobic) and different nitrogen (N) rates was evaluated in the semi-arid tropics, during 2009 to 2011. Associated irrigation water savings and N use efficiency was also compared between the two crop establishment methods. Influence of the establishment method of the preceding rice crop on growth, yield, nutrient uptake, water use, and water productivity of the subsequent no-till maize crop was determined.

Between the two rice establishment methods, flooded method of establishment resulted in greater leaf area index (LAI), higher dry matter, and higher yield over aerobic method of establishment. Flooded method also showed significantly higher yield associated factors such as spikelet number per panicle and 1000 grain weight (g). In aerobic rice, spikelet sterility was found to be a key reason for low performance when compared to flooded rice. Low yields in aerobic rice underscored the need for development of management strategies that can minimize yield suppression due to varied and dynamic factors.

The main advantage that aerobic rice had over flooded rice was the reduction in irrigation water usage. The number of irrigations scheduled during the crop growth period was considerably lower in aerobic rice. Higher water productivity and water savings, anywhere from 37 to 45%, were observed in aerobic over flooded method. Enhanced water productivity with complementary water savings can encourage adoption of aerobic rice method in areas faced with water shortages and when water is not available in quantities adequate for lowland rice cultivation.

Water and N interactions in rice are well studied topics in many parts of the world. Converting flooded rice to water saving systems such as aerobic system has resulted in high N losses accompanied by up to 50% reduction in N use efficiency. Our study also showed poor N use efficiency (19.4%-22.5 %) with almost half of the applied N lost from the soil-plant system (48.6%-58.5%). The N content and N uptake by rice plants was lower in aerobic treatments than in flooded establishment method. Nitrogen use efficiency and grain yield in aerobic rice has to be considerably higher to convince farmers to adopt the technology.

Higher growth characters were recorded in no-till maize grown after aerobic rice compared to flooded rice. Improved soil physical conditions after aerobic rice resulted in significantly higher crop growth, development and yield attributes such as cob weight, grain number per cob, grain yields and N uptake in maize than in maize after flooded rice. Although yield levels were lower, a simple comparison between the two systems showed that water productivity in aerobic rice-maize was significantly higher than in flooded rice-maize system.

Yield potential of the aerobic rice establishment method can likely be realized through optimized management of water and N in aerobic rice fields. Conducting repeated field experiments trying to identify the optimum N and water requirements can consume significant resources. Crop simulation models can instead provide opportunities to identify best management options without the resource burdens. The DSSAT CERES-Rice and Maize model was calibrated and evaluated for current climatic conditions. This model was able to capture major water and nutrient related processes accurately for both management systems. The DSSAT- CERES Rice and Maize was used to test and develop best management practices for aerobic R-M to promote environmentally friendly agricultural practices. The DSSAT model predicted that yields of aerobic rice can be improved if N fertilizer can be applied in four installments along with frequent irrigation with small quantities of water.

The Telangana region of state of Andhra Pradesh, India, where the present study was conducted, overlies shallow hard rock aquifers and is a major rice growing area in the peninsular India. In this region, rice is cultivated in both wet and dry season under high energy intensive irrigation system, leading to drying up of irrigation wells and declining groundwater table. Aerobic method of rice establishment under these situations can provide sustainable rice production and reduce the pressure on deep aquifers. Studies on N budgets under changed rice establishments for these regions provided an insight into the possible consequences in N transformations and when extended to larger areas can be useful in decision making.

Nitrogen Budget

Nitrogen budget estimation has been used extensively to get an idea on different pathways of N cycle for various ecosystems. An N budget will help in estimating the possible N losses and/or gains in a particular cropping system. In the present study based on field and modeling approaches, N budget was constructed for flooded and water saving aerobic rice to evaluate the relative environmental impacts. Major N pathways in rice grown under both the systems were grouped into two major categories-N gains and N losses. The N gains included mineralization of organic matter and release of ammoniacal N, fertilizer N application, crop residue incorporation, and biological N fixation, while the N losses included crop removal, gaseous losses through ammonia volatilization and denitrification, leaching and immobilization of inorganic N

(Table 7-1). In flooded rice, the main possible loss mechanisms are denitrification and ammonia volatilization. Since fertilizer was incorporated into the soil, losses through volatilization were minimal. In aerobic rice, by virtue of the system, leaching will be the main loss mechanism of N. Further in aerobic rice during heavy rainfall events and during times of irrigation events, anaerobic conditions may prevail for some part of the rice crop growth. The nitrate released during these periods will be denitrified to N_2O or N_2 gas due to anaerobic conditions and will be lost to the atmosphere. As the mineralization rates are higher in aerobic system and if N release is not matched with crop requirements, potential N losses will be higher. Our field data indicated that only 21% of the applied N was taken up by the aerobic rice crop compared to 32% by the flooded crop. Conversion of flooded rice ecosystems to aerobic systems for water saving may reduce the production of methane (CH_4), an important greenhouse gas, but may result in increased N_2O production, another potential greenhouse gas. The higher nitrate leaching losses in in aerobic rice may also pose a higher risk of nitrate contaminations to ground waters as it is still a predominant source of drinking water. Hence, adoption of aerobic rice system may result in water saving but at the same time can result in excessive N losses. Therefore, proper understanding of N pathways and N budgets in these systems will help in weighing the trade-offs between water-saving, yields, N losses and fertility maintenance.

Watershed N Budgeting

Agricultural systems, especially rice ecosystems, play a central role in the N cycle. Increasing water shortages due to failures in monsoon rains and depletion of ground water levels have provided options such as cultivation of ice under aerobic systems but may have strong influence on N cycle in a particular location. Earlier various studies have conducted N budget analysis at the watershed level to obtain knowledge on N fluxes. In the present study, I too tried to quantify the N budget on a watershed scale in semi-arid tropics, mostly cultivating paddy under both aerobic and flooded rice systems. Cultivated fields in the watershed area consist predominantly of paddy fields with a plot-to-plot irrigation using groundwater. We tried to calculate the change in the mass of N within the system by calculating various N imports and export values drawn from the field experiments and simulation modeling. Major inputs in the watershed are mainly in chemical inputs through fertilizers and various exports in rice N-cycles, in both aerobic and flooded systems, through various gaseous and leaching losses. Nitrogen budget of Kothakunta watershed under both systems clearly demonstrated N inflows and outflows from the watershed (Figures 7-1 and 7-2). Nitrate export in the watershed is the major concern under aerobic system as 16.5 t season^{-1} of nitrate leached from the system. We calculated N removal via gaseous losses under both systems and determined that it plays a significant role as 16 t N season^{-1} in flooded and 12 t N season^{-1} in aerobic rice was lost through atmosphere. Nitrogen budgeting under different rice management systems is a useful tool to assess the N fluxes in agro-ecosystems, providing a readily communicable guidance to improve N management to make these systems N efficient and minimizing environmental impacts.

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Table 7-1. Nitrogen budget for a sandy loam soil planted with rice under both aerobic and flooded method. * indicate estimated values from models and literature.

Description	kg ha^{-1} season^{-1}	
	Flooded rice	Aerobic rice
Nitrogen gains		
Potential N mineralization	44*	75*
Inorganic N application	120	120
Soil profile N	42	38
Addition of crop residues	8	8
Irrigation water	1	0.5
Total	215	241.5
Nitrogen losses		
Crop Removal	108	77
Gaseous losses (Denitrification and volatilization)	44*	32*
Immobilization	11*	19*
Inorganic N in soil profile after crop harvest	32	28
Leaching	11*	45*
Total	206	201

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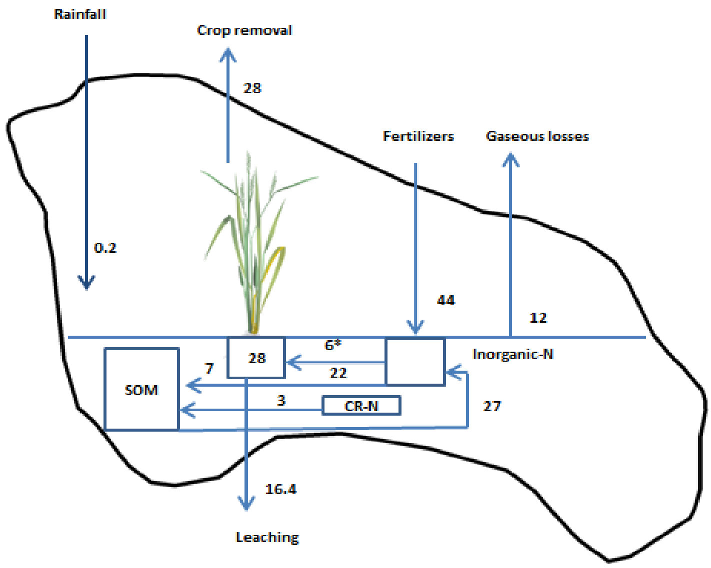

Figure 7-1. Schematic diagram representing the main aspects of N cycle in Kothakunta sub watershed lined with aerobic rice system. Boxes show the pools, arrows show flows in tonnes per season in watershed. * represents fertilizer derived N.

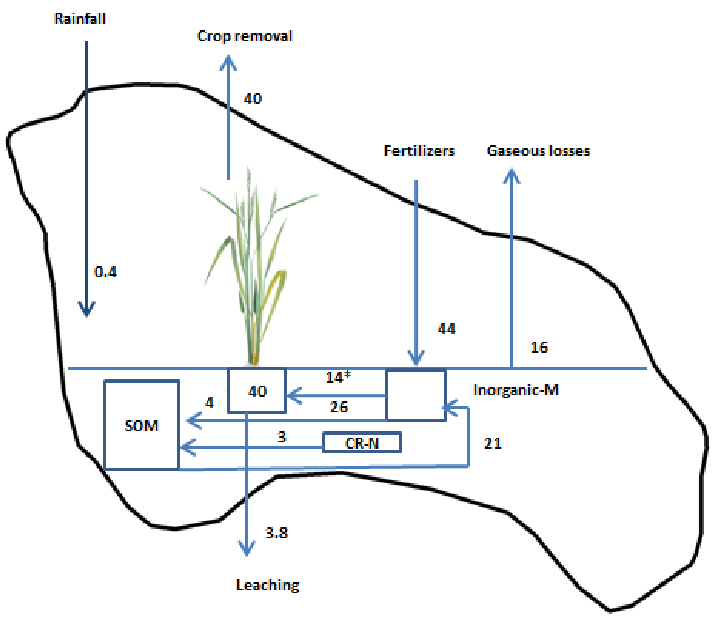

Figure 7-2. Schematic diagram representing the main aspects of N cycle in Kothakunta sub watershed lined with flooded rice system. Boxes show the pools, arrows show flows in tonnes per season in watershed. * represents fertilizer derived N.

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BIOGRAPHICAL SKETCH

Dakshina Murthy Kadiyala was born and brought up in Andhra Pradesh, India. After completing his school he joined Acharya NG Ranga Agricultural University, Hyderabad for his bachelor’s degree. He continued in the same university and completed master’s degree in agronomy. Immediately afterwards, he took the position of Assistant Professor at the Acharya NG Ranga Agricultural University, focusing on rice research. After working as assistant professor and research scientist for six years he joined Ph.D. in the Soil and Water Science Department at the University of Florida in 2008. After his graduation he plans to go back to India and continue his research on rice based cropping systems as a scientist in ANGRU.

Dakshina Murthy enjoys spending time with his wife Bhavani and two sons, Rohit and Rahul. They like travelling and watching movies.