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Integrated Soil, Water and Nutrient Management for Sustainable Rice–Wheat Cropping Systems in Asia

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INTEGRATED SOIL, WATER AND NUTRIENT MANAGEMENT FOR SUSTAINABLE RICE–WHEAT CROPPING SYSTEMS IN ASIA

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INTEGRATED SOIL, WATER AND NUTRIENT MANAGEMENT FOR SUSTAINABLE RICE–WHEAT CROPPING SYSTEMS IN ASIA

PREPARED BY THE
JOINT FAO/IAEA DIVISION OF NUCLEAR TECHNIQUES IN FOOD AND AGRICULTURE

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FOREWORD

Rice and wheat are intensively cultivated on over 20 million ha of land, of which 13.5 million ha are in the Indo-Gangetic plains and the remainder in China. The rice–wheat system is the predominant cropping system in Asia, providing food, employment and income, and ensuring the livelihoods of around one billion people. Since the 1990s, yield increases have kept pace with growing populations. However, the productivity of the current rice–wheat systems is seriously threatened by increasing land degradation and scarcity of water and labour, inefficient cropping practices, and other socioeconomic and environmental factors. Extensive tracts of productive cropland have also been taken over by rapidly growing urbanization and the associated infrastructure development. These factors, combined with the impacts of climate change, exacerbate the pressures on sustainable cereal production in the Asian region.

Conventional crop establishment methods and management practices followed in traditional rice–wheat systems need to be modified with the adoption of water and nutrient conserving technologies. This requires the development of alternative methods and improved practices that include elements of conservation agriculture aimed at producing more food and feed at higher income levels and reduced risk, using land, labour, water, nutrients and pesticides more efficiently than at present, and mitigating adverse impacts on the local and global environment.

A consultants meeting was organized by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture and held at the headquarters of the Food and Agriculture Organization of the United Nations, Rome, 23–25 August 2000, to review the issues and challenges in rice–wheat systems in Asia, to examine the role of nuclear techniques in water and nutrient dynamics studies and to prepare a draft proposal for a FAO/IAEA coordinated research project (CRP). Based on their recommendations, the IAEA CRP on the Integrated Soil, Water and Nutrient Management for Sustainable Rice–Wheat Cropping Systems in Asia was initiated in 2002 to study how to improve the productivity and sustainability of rice–wheat cropping systems through increased efficiency of water and nutrient use.

This publication contains eight papers prepared by the project participants, which explore the findings of the CRP. The IAEA officers responsible for this publication were L.K. Heng and J. Adu-Gyamfi of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

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SUMMARY

The Co-ordinated Research project (CRP) on "Integrated soil, water and nutrient management for sustainable rice–wheat cropping systems in Asia" (D1.50.07) established a research network and supported the efforts of teams of scientists in seven Member States with the overall objective of improving the productivity and sustainability of rice–wheat cropping systems through increased efficiency of water and nutrient use. The specific objective of the project was to modify existing water and nutrient management systems, and improve soil management in both traditional and emerging (raised beds, non-puddled soil, direct seeding) crop establishment methods for sustainable intensification of cereal production in Asia.

Overall, rice and wheat yields are decreasing in many areas because of declining soil organic matter and nutrient status, increasing salinization and deteriorating soil physical conditions. Soils in most of the intensively cultivated rice–wheat growing areas are low in soil organic matter and have low nitrogen (N) availability. High inputs of N fertilizer are commonly used in rice–wheat systems to achieve good plant growth and adequate grain yields. Efficient management of N fertilizers is one of the key approaches to obtaining a higher economic crop yield, increasing use efficiency of N and reducing N fertilizer loss through various means to protect land and water resources and promote environmental sustainability. The main loss pathways for N fertilizers are leaching, denitrification and ammonia volatilization. The loss of nitrous oxide (N_2O) gas is of major importance as it is a major contributor to global warming, being 310 times more effective in trapping heat in the atmosphere than CO_2. Loss of nitrate (NO_3^-) through leaching can have severe environmental consequences particularly on the quality of drinking water. It is of great importance to optimize the availability of any added N fertilizer to crops not only because of the environmental pollution that N losses can cause but also because of the continuous increase in fertilizer prices. The prerequisite of such a management system, however, is to quantify the dynamics and losses of N at field, farm, and regional scales. The use of ^{15}N labelled fertilizers can aid in quantifying plant N uptake and N fertilizer recovery in the soil–plant system. This enables the calculation of nitrogen use efficiency (NUE) and an estimation of the losses of the added N fertilizer from the system.

In many areas of Asia and Australia, the availability of irrigation water is decreasing while water costs are increasing, making improved water use efficiency (WUE) an issue of major importance in these irrigated systems. Neutron probes can be used to monitor soil water status and aid in determining crop water use and increasing water use efficiency in cropping systems, particularly in non-flooded situations.

Phosphorus (P) is another nutrient limiting crop productivity and major fertilizer inputs are required in rice–wheat systems for optimum plant growth and grain yields. Rapid changes in soil water conditions from flooded to non-flooded have a great influence on soil redox changes from reduced to oxidized (aerobic) conditions as well on predominant P compounds and their dynamics. In earlier experiments conducted in Australia, poor pasture growth following rice was found to be caused by a lack of plant available P resulting from P adsorption onto active sites, which had been exposed by the flooding conditions imposed in the rice crop. To improve P fertilizer management there is a need for better understanding of the processes that control P availability to plants in these alternating aerobic-anaerobic soils. The isotopes, ^{33}P and ^{32}P, allow the separation of native soil and fertilizer P sources, which is necessary for the understanding of these processes.

The main findings and conclusions arising from the CRP are summarized under four main headings. The first section deals with the characterization of the studied rice–wheat systems, approaches followed and the main soil and climatic conditions under which the

experiments were conducted. The second section describes the rice–wheat crop performance in terms of yield and nitrogen uptake over the years at the experimental sites of the CRP. The third section, reports on ecosystem service efficiency, in particular nitrogen and water use efficiency in rice–wheat cropping systems. The final section includes concluding remarks arising from the project studies.

1. CHARACTERIZATION OF RICE–WHEAT CROPPING SYSTEMS

Conventional method for rice–wheat cultivation includes growing rice during the summer season (May–June through September–October) and wheat during the winter season (November–April) in a continuous sequence of crop rotation. About two thirds of the total rice production is grown under irrigation. The conventional irrigation system for rice is to flood and maintain free water in the field. Initial flooding provides favourable conditions for land preparation, rapid crop establishment at transplanting and efficient weed control. However tillage and puddling the soil in a saturated state destroys the soil structure and can result in the formation of hard pan layers at 15–30 cm depth. Continuous flooding results in anaerobic conditions, which provide good growth conditions to lowland rice in terms of water and nutrient supply. However this conventional system uses a large amount of water with high losses due to evaporation, seepage and percolation. When the soil dries after harvesting the rice crop, cultivation for the following wheat crop is difficult and often results in a poorly prepared cloddy seedbed with limited soil seed contact, poor seedling emergence and reduced yields. Rice residues are often burned due to time and labour constraints for planting wheat.

There are a large number of possible combinations of conventional crop establishment methods and related management practices in terms of tillage, crop layout, crop planting / seeding, crop residue management, and water regime (Table 1). There is increasing interest in the use of water saving systems such as raised beds that offer the possibility of furrow irrigation instead of flood irrigation and aerobic rice systems (well-watered aerated conditions).

Conventional flooded (and puddling) methods followed in rice–wheat systems need to be modified with adoption of resource conservation technologies for higher production, income, sustainability, resource use efficiency, and adaptation to climate change and climatic variability. This would involve the development of alternative crop establishment methods and improved cropping practices that include elements of Conservation Agriculture aiming at producing more food and feed at higher income levels and reduced risk, improving the use of land, labour, water, nutrients, and pesticides more efficiently than at present and mitigating adverse impacts on the local and global environment. The CRP on Integrated Soil, Water and Nutrient Management for Sustainable Rice–wheat Cropping Systems in Asia, was designed to investigate the impact of selected innovative crop establishment methods for growing rice and wheat in these areas on crop yields and their effects on nitrogen use efficiency (NUE) and water use efficiency (WUE).

TABLE 1. CROP ESTABLISHMENT METHODS AND RELATED CROP MANAGEMENT PRACTICES IN STUDIED RICE–WHEAT CROPPING SYSTEMS

Crop establishment methods / management practices	Rice	Wheat
Tillage / land preparation	Tillage and non-tillage Puddling and non-puddling	Tillage and non-tillage
Seeding / planting	Direct seeding / Transplanting	Direct seeding
Crop layout	Flats /raised beds (temporary/ permanent)	Flats / raised beds (temporary/ permanent)
Crop residue management	Removal / burning/ Mulch / incorporation	Removal / burning/ Mulch / incorporation
Crop water regime	Flooded / Non-flooded: Saturated soil culture / Aerobic	Aerobic
Weed control	Chemical / manual/mechanical	Chemical / manual / mechanical
Fertilizer N management	Single / split application	Single / split application
Water management	Rainfall / Irrigation (Continuous and intermittent / Furrow / ponds) Rainfall + irrigation	Rainfall / Irrigation / Rainfall + irrigation

Field experiments were set up at the following sites: Ludhiana in North-western India (Singh et al.); Meherpur, Bangladesh (Khan); Sichuan (Pan et al.) and Nanjing (Shen et al.), China; Ranighat, Nepal (Munankarmy and Sah); Lahore, Pakistan (Hussain et al.) and Griffith, South-eastern Australia (Mathews et al.). The experimental sites were located between the latitudes of 34.3°S (Griffith, Australia) and 33.5°N (Nanjing, China) and longitudes of 74.0 and 146.0°E. The altitudes ranged from 7 to 540 m above mean sea level (Table 2). The mean maximum and minimum temperatures during the rice season were 26.8 to 34.3°C and 14.6 to 26.8°C, respectively, and in the wheat season were 15.4 to 28.0°C and 8.1 to 15.5°C, respectively. Average annual rainfall across the sites ranged from 88 to 1646 mm in the rice season and 76 to 884 mm in the wheat season. In terms of soil fertility the sites varied widely in soil organic C concentration, ranging from 4.5 to 12.0 g kg^{-1}, total N from 0.4 to 1.7 g kg^{-1}, and pH from 5.8 to 8.4. Textural classes of surface soil were sandy loam to clay (Table 3).

At the field sites in Ludhiana, India, Meherpur, Bangladesh, Ranighat, Nepal and Lahore, Pakistan, the effects of using permanent raised beds under aerobic conditions with either transplanted or direct seeded rice followed by direct seeded wheat were compared with conventional flooded systems with transplanted seedlings and conventional cultivation before sowing wheat. A system of zero till rice and wheat was also studied. The field experiments in Sichuan and Nanjing, China investigated the effect of using aerobic rice cultivation with either plastic or straw mulch, which was compared to conventional flooded systems. N dynamics under furrow irrigated rice in permanent raised beds using ^{15}N labelled urea at several N rates and different split applications compared to a single application were investigated in the field experiment in Griffith, Australia. All the field experiments used ^{15}N labelled fertilizer in micro plots, for studying the impact of integrated soil, water and nutrient management on fertilizer N recovery and balance in rice–wheat cropping systems.

TABLE 2. LOCATION AND CLIMATIC CONDITIONS DURING RICE AND WHEAT SEASONS AT THE EXPERIMENTAL FIELD SITES IN ASIA AND AUSTRALIA

Site	Latitude / longitude	Altitude (m asl)	Rice			Wheat		
			Rainfall (mm)	Temperature (°C)		Rainfall (mm)	Temperature (°C)	
				Maximum	Minimum		Maximum	Minimum
Meherpur, Bangladesh	25.8°N / 88.2°E	15	1090	32.2	24.5	98	28.0	14.8
Ludhiana, India	30.9°N / 75.9°E	247	571	34.3	22.4	141	23.6	10.7
Ranighat, Nepal	27.0°N / 84.6°E	112	1646	32.9	26.8	88	25.8	15.5
Lahore, Pakistan	31.0°N / 74.0°E	214	282	33.6	24.4	143	24.5	13.5
Sichuan, China	30.8°N / 103.8° E	540	610	28.6	21.0	177	15.4	8.1
Nanjing, China	33.5°N / 120.2°E	7	918	26.8	19.6	n/a	n/a	n/a
Griffith, Australia	34.3°S / 146.0°E	116	880	31.2	14.6	n/a	n/a	n/a

n/a, not available

TABLE 3. SELECTED SOIL (0–15 cm) CHARACTERISTICS AT THE EXPERIMENTAL FIELD SITES IN ASIA AND AUSTRALIA

Site	Textural class	pH	Organic C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	CEC ($cmol^{+}\ kg^{-1}$)	Olsen-P ($mg\ kg^{-1}$)	Exch. K ($mg\ kg^{-1}$)
Meherpur, Bangladesh	Silty loam	8.4	7.8	0.7	6.4	29	47
Ludhiana, India	Sandy loam	7.8	4.5	0.4	13.5	11	60
Ranighat, Nepal	Loam	5.8	8.0	0.5	8.0	11	15
Lahore, Pakistan	Clay loam	8.0	9.6	1.2	n/a	n/a	n/a
Sichuan, China	Clay	6.8	12.7	1.7	18.0	18	38
Nanjing, China	Loam	8.4	12.0	0.7	14.1	5	90
Griffith, Australia	Clay loam	6.0	12.0	1.0	35.0	n/a	n/a

CEC, cation exchange capacity; n/a, not available

2. CROP PERFORMANCE

2.1. GRAIN YIELDS

2.1.1. Rice

Rice yields over the three years varied across the different sites and with the various crop management practices. The highest average yield of rice over the three years of the experiment was recorded in Sichuan, China (7.70 t ha^{-1}) followed by Jiangsu, China (6.62 t ha^{-1}) and Ludhiana, India (6.4 t ha^{-1}) for puddled transplanted rice. The lowest yields were for no till direct seeded rice on permanent beds at Meherpur, Bangladesh (2.8 t ha^{-1}). Grain yields of rice at all the sites were affected by crop management practices and the conventional puddled, transplanted rice produced the highest yields. At Meherpur, Bangladesh, Ludhiana, India and Ranighat, Nepal, grain yields of rice declined significantly over the three years under direct seeding and bed transplanting compared with rice transplanted into puddled soil. Weed infestation was one of the most severe problems in the direct seeded rice and more effort is needed to control weeds to increase rice yields under direct dry seeding.

2.1.2. Wheat

Grain yields of wheat were also affected by crop management practices. The highest grain yield of wheat averaged over the three years was recorded at the site in Sichuan, China

(4.86 t ha^{-1}), while the lowest average yield was at Meherpur, Bangladesh for direct drilled wheat (2.2 t ha^{-1}). Unlike rice, conventional flatbed tilled and no-till wheat produced similar yields in all the sites and puddling and non-puddling of soil in the previous rice crop had no effect on the subsequent wheat crop. Data from these diverse sites indicates that wheat can be grown with zero tillage in a rice–wheat system without any yield penalty.

2.2. UPTAKE OF N

2.2.1. Rice

Uptake of N by rice was affected by the crop management practices. The highest N uptake in the conventional puddled transplanted system was recorded at the Sichuan, China site (152 kg N ha^{-1}) followed by the Lahore, Pakistan site (105 kg N ha^{-1}), averaged over three years. Other crop management practices had lower N uptake compared with conventional puddled transplanting.

2.2.2. Wheat

Uptake of N by wheat was also affected by crop management practices. Higher N uptakes were recorded in Sichuan, China (120 kg N ha^{-1}) and Lahore, Pakistan (117 kg N ha^{-1}) compared to the other sites. Conventional flatbed tilled and no till wheat produced similar N uptake in the Ludhiana, India and Ranighat, Nepal sites. These data, along with the data on yield recorded at different sites, indicate that wheat can be successfully grown with zero tillage in a rice–wheat system.

3. RESOURCE USE EFFICIENCY IN RICE–WHEAT CROPPING SYSTEMS

3.1. NITROGEN USE EFFICIENCY

Estimated N fertilizer losses in rice as determined by the ^{15}N mass balance technique were high at many of the sites. In the experiments comparing conventional puddled, flooded rice with raised beds and zero till, losses ranged from 36% in the conventional puddled, flooded system in Ranighat, Nepal to 58% in the zero till system in Meherpur, Bangladesh, and the transplanted raised bed system in Ludhiana, India averaged over the three rice crops. Estimated N fertilizer losses in wheat averaged over the three years ranged from 13% in the conventional cultivation following puddled, flooded rice in Ludhiana, India to 56% in the zero tillage system at Ranighat, Nepal.

At Sichuan, China, the difference in NUE for NH_4^+ and NO_3^- based fertilizers was investigated using ^{15}N labelled fertilizers. The recovery of N fertilizer was higher for the NH_4^+ based fertilizer than from the NO_3^- based fertilizer. At Nanjing, China two methods were used to determine NUE, the non–isotopic difference method and the ^{15}N isotopic method. Results showed that NUE values were lower using the isotopic method compared to the non-isotopic (difference) method. When using the difference method no distinction can be made between native soil N and fertilizer N, which means that NUE can often be overestimated and losses underestimated.

At Griffith, Australia, split applications improved NUE when compared to a single application with losses in the split system being 32% compared to 46% for the single application system. At this site, rice yields in the ^{15}N micro-plots were compared to those in the main plots. It was shown that, except for one treatment where the yield in the micro-plot was higher, the differences between the yields for the micro-plots and the main plots were not more than 10%. The reason for the one exception could not be explained.

3.2. WATER USE EFFICIENCY

WUE estimates varied across sites. Generally permanent raised beds used less water than conventional flooded systems but on some sites the WUE was higher for the flooded systems than the bed systems. This was the result of the low yields shown on direct drilled permanent beds. The longer duration of the direct drilled crops compared to flooded crops also affected the WUE as these crops required irrigation for longer periods.

In China, the use of mulching resulted in increased WUE, as yields under this system did not suffer such dramatic yield decreases. Neutron probes were used to monitor soil moisture and crop water use at two sites, Sichuan, China and Ludhiana, India. At both sites differences in soil moisture were recorded between different treatments and at the site in Ludhiana, India, the neutron probe measurements showed that the wheat crop extracted water to a depth of 180 cm. Further studies using neutron probe soil moisture measurements to schedule irrigation events could help to increase water use efficiency in non-flooded systems.

4. SUPPORTIVE RESEARCH

A series of glasshouse experiments were conducted at the University of New England, Armidale, Australia to investigate the influence of acidulated rock silicate on P dynamics under flooded and non-flooded conditions using P isotopes. The studies indicated that considerable potential exists to increase P use efficiency in rice–wheat systems where soils change from flooded to non-flooded conditions and in continuously non-flooded soils. For instance the application of acidulated rock silicate (ARS) resulted in small but variable rice yield increases when applied with P fertilizer. Further investigations on the impacts of ARS materials in these systems, which change from flooded to non-flooded may provide a better understanding of factors influencing P dynamics to improve soil P availability to plants. The degree and process of acidulation of rock silicates requires considerably more research and the combined use of ^{32}P and ^{30}Si will greatly assist this research. Difficulties in the determination of ^{30}Si need to be overcome for this to be possible.

5. CONCLUDING REMARKS

The main results obtained from this CRP provided relevant information on the application of nuclear and isotopic techniques to gain an improved understanding of resource (nitrogen and water) use efficiency in rice–wheat systems grown with emerging crop establishment methods to improve sustainable intensification of cereal production in Asia.

The extensive use of ^{15}N in all field experiments over the seasons and years allowed for the tracing of the N through the system and quantification of fertilizer N recovery in plants and soil and the estimation of the amount of fertilizer N, which had been lost from the soil–plant system. Nitrogen losses from ^{15}N-labelled fertilizer were at least 10% higher under aerobic conditions compared to the conventional flooded system. Thus any potential water savings should be considered against the reduction in grain yield and the losses of fertilizer N. Regardless of the growing conditions, the efficiency of utilization of fertilizer N in rice or subsequent wheat crops did not exceed 60%, suggesting that effective N management to increase use efficiency of fertilizer N and reduce losses continues to be a top research priority in these high input cropping systems. As NUE was in general relatively low to medium in the studied cropping systems, this indicates that applied N exceeds crop yield potential.

At two sites, Sichuan, China and Ludhiana, India; soil moisture neutron probes were used to monitor volumetric soil water content in the soil profile and crop water use between different crop management treatments. At the site in Ludhiana, India, the neutron probe measurements showed that the wheat crop extracted water to a depth of 180 cm. during the dry season. Further studies using neutron probe soil moisture measurements to schedule irrigation events could help to increase water use efficiency in non-flooded systems.

It was found that there was no loss of yield when rice was grown in aerobic soil in areas where annual rainfall was over 800–1200 mm and straw mulching was practiced. However in situations with lower annual rainfall, the existing paddy rice varieties produced lower yields on furrow irrigated raised beds compared to the traditional flat flooded beds. Grain yield of wheat was also affected by crop management practices. Data from these diverse sites indicates that wheat can be grown with zero tillage in a rice–wheat system without any yield penalty.

With regard to the use of emerging crop establishment methods for the sustainable intensification of rice–wheat systems, several issues were raised. Many researchers reported that new varieties better adapted to permanent bed systems and aerobic rice culture will need to be developed to cope with the increasing incidence of water scarcity. From physiological studies it is reported that lowland rice genotypes are sensitive to small water deficits. Thus, it is critical to develop rice cultivars that can tolerate moderate water deficits for use in water saving rice systems. Proliferation of weeds proved to be the biggest problem causing reduced yields in the direct seeded rice crops. Further research on weed control and suitable herbicides is essential if this type of practice is to become viable. Nematode infestations also proved to be a severe problem at some sites and were exacerbated by the use of mulching in Sichuan, China. Poor soil surface conditions also appeared to cause reduced seedling emergence from direct seeding and this may be overcome by using residue return to try and improve surface soil conditions, but nematode control will also need to be taken into account. Row spacing and sometimes reduced seeding rates used on raised beds also caused yield reductions and further research studying different row spacing, seeding rates and particularly furrow widths could help to increase yields in raised bed systems. The transformation of the conventional R–W systems is also labour intensive and demands careful management to obtain the expected benefits. Imbalanced use of nutrients, especially N, P and K, and increasingly S, Zn and Fe deficiencies are widespread in intensively cultivated R–W systems in Asia. Tools are currently being developed to identify and correct these nutritional imbalances.

Diversification of rice–wheat cropping systems in Asia is highly desirable, but this was not a specific research objective of the CRP. Permanent furrow irrigated raised beds offer opportunities for crop diversification and intercropping. New viable cropping alternatives should be explored. Further research work utilising an integrated approach to crop, soil, water and nutrient management in long-term field studies is needed to overcome the problems and limitations mentioned above, and thus the expected yield potential and improved NUE and WUE may be able to be achieved with rice grown under direct seeded, permanent bed systems, which over time are likely to result in increased yields for the following wheat crop and lower N losses to the environment.

NITROGEN AND WATER USE EFFICIENCY AND CROP PRODUCTIVITY EVALUATION OF A RICE–WHEAT CROPPING SYSTEM USING DIFFERENT CROP ESTABLISHMENT TECHNIQUES IN BANGLADESH

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Abstract

In the Indo-Gangetic Plains of Bangladesh, the cultivated area of rice–wheat cropping systems is over 13.5 million ha, covering about 6% of the cropland. In this dominant cropping system, over 85% of the wheat is cultivated in rotation with transplanted Aman (T. Aman) rice, which grows from July to December. In order to achieve food security of the rapidly growing population, there is an urgent need to boost productivity of rice–wheat systems in the country. Field experiments were conducted during the period 2002–2006 to evaluate the productivity of a rice–wheat system under conventional and permanent raised bed planting in a farmer's field in South-west Bangladesh. There were 5 treatments (crop establishment and tillage) for each rice and wheat crop with four replications arranged in Randomized Complete Blocks. Each main plot contained a micro plot for applying ^{15}N labelled urea as a tracer fertilizer. Fertilizer application rates were 100–46–40–10–4 and 120–60–60–4 kg of N, P_2O_5, K_2O, S and Zn kg ha^{-1} for rice and wheat, respectively. Conventional planting (PTFS/CT) produced the highest grain yield for both rice and wheat. Irrespective of crop establishment techniques, yields of rice and wheat decreased over time. Yield was reduced with raised bed plantings (UPTB/D and UPDB/D), while zero tillage cropping (UPDF/D) resulted in the lowest yields. Irrigation water savings for raised bed planting and zero tillage were 24 and 54% for rice and 24 and 14%, respectively, for wheat compared to conventional planting (PTFS/CT). The mean total N uptake was 12% less in raised bed planting and 22% less in zero tillage. Nitrogen derived from fertilizer (% Ndff) for the rice crop was higher in raised bed planting and zero tillage but there was no difference for the wheat crop. ^{15}N fertilizer recovery by rice ranged from 27 to 37% with the crop establishment techniques. The total ^{15}N fertilizer recovery in rice and soil ranged from 41 to 50% and the estimated ^{15}N fertilizer losses (unaccounted for N) from the rice–soil system varied from 50 to 59%. ^{15}N fertilizer recovery by wheat was low and varied from 16 to 20% with the crop establishment method. The total ^{15}N fertilizer recovery in the wheat and soil ranged from 63 to 69% and the estimated ^{15}N fertilizer losses from the wheat–soil system varied from 31 to 37%. At the rice–wheat system level, ^{15}N fertilizer recovery by rice and wheat ranged from 20–26% with the various crop establishment techniques and tillage practices over the experimental period. Total productivity of the rice–wheat system decreased over time. The productivity declined by 10 and 13% for raised bed planting (UPTB/D and UPDF/D), respectively, and by 24% for zero tillage (UPDF/D). This yield decline appeared to be the result of poor seedling emergence, high weed infestation and could also have been the result of using unsuitable varieties. Further research adopting an integrated approach to crop, soil, water and nutrient management is needed before zero tillage and direct seeding technology can be successfully introduced and contribute to the development of sustainable rice–wheat cropping systems.

1. INTRODUCTION

In the Indo-Gangetic Plains of Bangladesh, the cultivated area of rice–wheat cropping systems is over 13.5 million ha, covering about 6% of the cropland [1]. In this dominant cropping system, over 85% of the wheat is cultivated in rotation with transplanted Aman (T. Aman) rice, which grows from July to December [2, 3]. Recent analysis of long term research has indicated that yields are decreasing in these cropping systems [4]. A rapidly growing population is putting additional pressure on the limited arable land area due to increased urbanization and infrastructure development. Consequently, the per capita land is gradually declining. It is estimated that the population of Bangladesh will increase from the present level of approximately 140 million to 169 million inhabitants by the year 2025. In this context, to feed this rapidly growing population there is an urgent need to boost productivity of rice–wheat systems in the country.

In rice–wheat systems, the soil and water requirements of the two crops are quite different. Rice seedlings are traditionally transplanted into thoroughly puddled and submerged soils, while wheat requires a well pulverized and aerated soil to attain its potential yield. Puddling eases rice transplanting, conserves water, control weeds and enhances the availability of macro and micronutrients. However, puddling also creates soil conditions that are unfavourable for the following wheat crop. After the rice harvest, puddled soils dry out quickly, presenting cracks and increases in bulk density. Compacted pan layers often develop in puddled rice soils at varying depths between 15–40 cm depending on soil texture and tillage [5, 6]. After rice, when the soils are dry-tilled, they generally break into large clods with a high tensile strength and become hard and difficult to achieve a fine tilth. Wheat establishment in these cloddy soils is difficult and results in poor wheat yields [7, 8]. Compacted layers also limit water infiltration following rainfall or irrigation leading to temporary water logging problems and reduced aeration in the root zone. Poor soil aeration is the most limiting factor for wheat cultivation following rice. Crop establishment techniques that would create favourable soil–water conditions for the crops in the rice–wheat systems are essential for increasing and sustaining high yields in both crops.

"Aerobic rice" is a novel system in which rice is grown as an upland crop but with high inputs and an assured continuous irrigation supply. In recent years, direct seeding of rice has been reported as an alternative to puddled transplanted rice. Raised bed planting, a new tillage and crop establishment technique, has been evaluated by different institutes of the National Agricultural Research System (NARS) under the umbrella of the Rice–wheat Consortium of the Indo-Gangetic Plains as a means to improve resource use efficiency [7, 8, 9, 10, 11, 12]. The aerobic cultivation of rice on raised beds and flat beds are alternative crop establishment techniques that do not create the same constraints as puddled soils, for the following wheat crop. However, the effect of new crop establishment methods such as raised bed plantings on the rice–wheat productivity at the field level is not known.

Low soil N availability is the main factor limiting the productivity of rice–wheat systems. Thus high fertilizer N inputs should be applied to ensure good growth and adequate production of both crops. Improving irrigation water management is also a matter of prime concern because of water scarcity, high irrigation costs and emerging environmental issues. The use of novel crop establishment techniques would demand the development of appropriate fertilizer N and water management practices to increase their use efficiency for increasing and sustaining the productivity of the rice–wheat systems. Considerable research work has been conducted for rice and wheat crops grown in isolation, but information is scanty on resource use efficiency, in particular N use efficiency and N losses at the cropping system level. Quantitative estimates of these issues related to N use efficiency can be obtained using the ^{15}N isotopic tracer methodology [13].

Field experiments were conducted to make a comparative evaluation of the conventional and raised bed planting on the productivity of a rice–wheat cropping system, in particular their effects on N fertilizer and water use efficiency in Bangladesh. The ^{15}N isotopic technique was utilised to determine crop fertilizer N uptake, total N recovery in the soil–plant system and to estimate fertilizer N losses from the system.

2. MATERIALS AND METHODS

2.1. EXPERIMENTAL SITE

The field experiments were conducted during the period 2002–06, with IAEA financial support in a farmer's field located in the village of Chandbil, district of Meherpur, South-Western Bangladesh. The study was also linked to the research work of the Rice–wheat Consortium (RWC). The experiments started with the wheat crop of the 2001–02 Rabi season (November–March).

Selected soil physical and chemical characteristics (0–45 cm) of the experimental site are presented in Table 1. The soil is moderately alkaline and uniform throughout the profile, the textural class is silty clay with a predominance of fine soil particle fractions and the soil fertility status decreases with depth.

TABLE 1. INITIAL SOIL CHARACTERISTICS OF THE EXPERIMENTAL FIELD, MEHERPUR, BANGLADESH

Depth (cm)	pH	Particle size (g kg^{-1})			Property (g kg^{-1})		(mg kg^{-1})			($cmol^+$ kg^{-1})	
		Sand	Silt	Clay	OM	Total N	P	S	B	Exch. K	CEC
0–15	8.5	120	650	230	25	1.2	29	14.7	0.5	0.12	8.0
15–30	8.4	150	620	230	16	0.8	14	12.3	0.5	0.10	7.2
30–45	8.4	150	650	200	13	0.7	9	11.3	0.3	0.09	6.4

Texture (0–45 cm) is silty clay; OM, organic matter; CEC, cation exchange capacity

2.2. CLIMATIC DATA

Monthly climatic data (rainfall and temperature) and sunshine hours during the whole experimental period (years 2002–06) were collected from a nearby weather station. Rainfall is given in Fig. 1, temperature in Fig. 2 and sunshine hours in Table 2.

Year to year rainfall (total and distribution pattern) variations were observed. Wet months with >200 mm rain began from May in 2002, but in subsequent years the start of the wet season was later. Very high rainfall, 764 and 572 mm occurred in September and October in the years 2004 and 2005, respectively. Rainfall during November to February (dry season) was nil. The dry season was sometimes longer than normal. Cool periods and the length of these periods are crucial for wheat production. In Bangladesh, wheat crops usually flower after 1 November and mature during March. The average maximum temperature was about 1°C higher than average, during February in 2005 and about 2°C higher in 2006 (Fig. 2). Average minimum temperature was also higher, by more than 3°C during anthesis, grain filling and the ripening phase of the wheat crop. Wheat growth and yields were severely affected by the higher night temperatures, which prevailed during the reproductive and ripening phase for the last two years of the project.

TABLE 2. TOTAL MONTHLY SUNSHINE HOURS, MEHERPUR, BANGLADESH, 2001–06

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	217	211	250	248	223	129	145	162	159	197	189	188
2002	210	242	169[a]	252	203	157	91	133	171	241	226	227
2003	203	207	235	252	172	155	154	185	149	150	254	208
2004	185	238	254	237	256	138	158	189	145	236	251	224
2005	188	240	255	272	251	170	129	124	187	150	239	244
2006	200	201	253	241	271	–	–	–	–	–	–	–

[a]Data for 20 days only

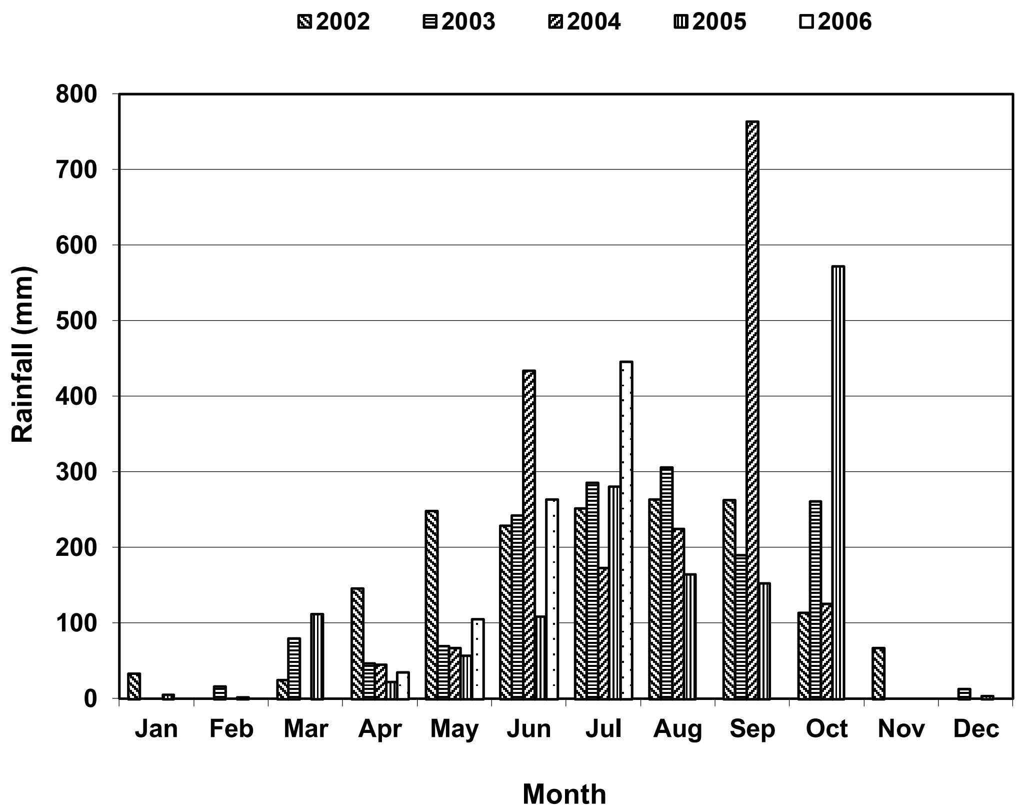

FIG. 1. Monthly rainfall (mm) over the years 2002–06, Meherpur, Bangladesh.

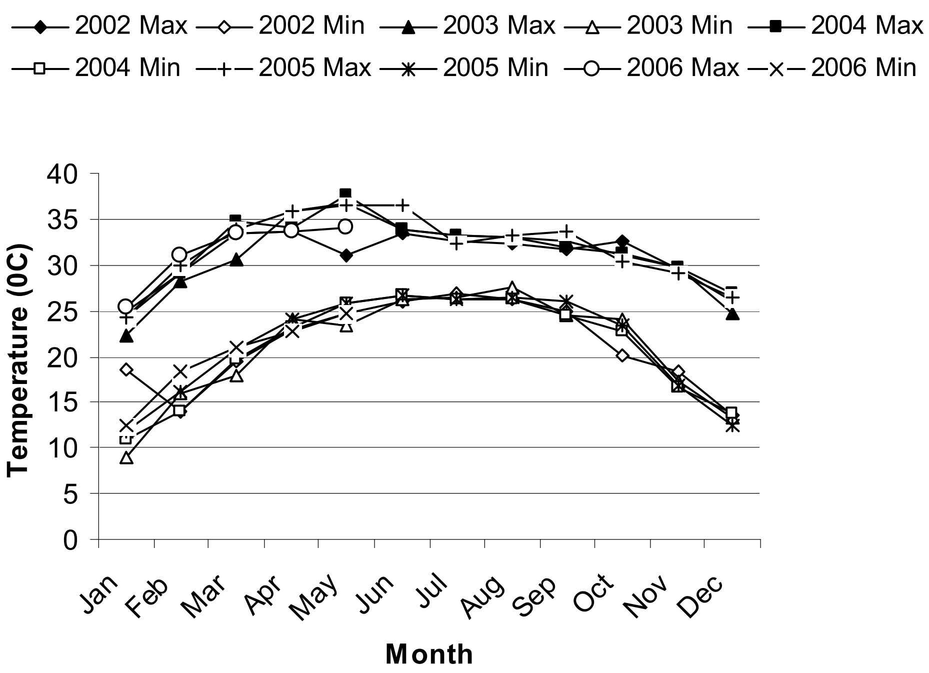

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FIG. 2. Minimum and maximum monthly temperature over the years 2002–06, Meherpur, Bangladesh.

2.3. EXPERIMENTAL DESIGN/TREATMENTS

There were five different treatments for each rice and wheat crop. Wheat was grown following rice. A detailed description of the treatments for the two crops is given in Table 3.

TABLE 3. TREATMENT DESCRIPTION OF THE EXPERIMENT, MEHERPUR, BANGLADESH

Treatment	Rice	Wheat
PTFS/CT	Transplanting on puddled flatbed (20 × 20 cm spacing)	Sown on well pulverized flat bed in lines 20 cm apart
PTFR/CT	Transplanting on puddled flatbed (20 × 30 × 20 cm; plant to plant 7–8 cm)	Sown on well pulverized flatbed (20 × 30 × 20 cm)
UPTB/D	Transplanting on unpuddled raised permanent bed (20 × 30 × 20 cm; plant to plant 7–8 cm)	Sown on raised (permanent) bed (20 × 30 × 20 cm)
UPDB/D	Direct dry seeding on unpuddled raised bed (permanent) (20 × 30 × 20 cm)	Sown on raised (permanent) bed (20 × 30 × 20 cm)
UPDF/D	Direct seeding on unpuddled (zero tilled) flatbed (20 × 30 × 20 cm)	Sown on zero tilled flatbed (20 × 30 × 20 cm)

Treatments were arranged in Randomized Complete Block Design (RCB) with four replications. There were 20 plots in total and each plot measured 9 x 9 m (81 m^2).

Raised bed planting, a new tillage and crop establishment technique, was included in the experiment and the concept of "permanent beds" was adopted. The raised beds established at the beginning of the 2001–02 Rabi season wheat crop were retained and only a small amount of renovation (reshaping) of the beds was done manually with a spade before planting each crop. Normal land preparation was done as per the treatment description for both rice and wheat. No tillage (unpuddled) was used for both rice and wheat in UPTB/D, UPDB/D and UPDF/D. Before planting the wheat, a non-selective herbicide was applied during the first two seasons. A hand rake consisting of a single tine was used for making two lines (strip tillage) for seeding. Seeds were hand drilled.

In each main plot, there was a micro plot measuring 0.8 m^2 (0.8 × 1.0 m) for the flat bed and 0.804 m^2 (0.67 × 1.2 m) for the raised beds. Micro plots, for the application of ^{15}N labelled fertilizer, were constructed by putting a metal frame into the soil using a wooden block and heavy hammer. These were embedded into the soil to a depth of 25 cm and were 10 cm above the soil surface. Micro plots were laid down at different sites within the main plots for the rice and wheat crops. The sizes of the metal frames were 100 × 80 × 40 cm and 120 × 67 × 55 cm for flat and raised beds, respectively. ^{15}N labelled urea (5 atom % ^{15}N excess) was applied after dissolving in water to each micro plot using the recommended N rate (see Tables 4 and 5) for rice and wheat, respectively.

2.4. FIELD AND CROP MANAGEMENT

Field management practices used for the rice and wheat crops are presented in Tables 4 and 5, respectively. A rice variety BRRIdhan39 developed by the Bangladesh Rice Research Institute (BRRI) for the T. Aman season was used and a wheat variety Kanchan developed by the Bangladesh Agricultural Research Institute (BARI) was grown following the rice harvest. Dry seeding of rice took place between June 30 and July 11 and transplanting was done between 27 July and 12 August (Table 4). N, P_2O_5, K_2O, S and Zn were applied at rates of 100–46–40–10–1.5 and 120–60–60–10–1.5 kg ha^{-1} for rice and wheat, respectively, using prilled urea, triple superphosphate, muriate of potash, gypsum and zinc sulphate. All fertilizers except N were applied as a basal. N fertilizer was applied in four equal splits in rice and three splits in wheat: the first split as basal and the others as top-dressing (Tables 4 and 5, respectively).

All plots were irrigated on the same day and irrigation occurred when hair-like cracks appeared in the absence of rainfall in the flat beds of the rice crop. The amount of water applied for each irrigated plot was measured by using a 'V-Kontoch' device. Four irrigations were given in the wheat crops except for the 2005–06 wheat crops where an extra irrigation was required. The total number of irrigations in the rice crop varied from 5 to 6 and during 2005 an extra irrigation at transplanting and direct seeding was necessary.

Rice yield was adjusted at 14% moisture content and wheat yield at 12% moisture content. Dates of wheat planting varied from 22–27 November and harvest maturity dates ranged from 10–24 March (Table 5). The wheat crop maturity was two weeks earlier during the last two seasons because of unfavourable temperatures. Seeding of wheat took place in the last week of February and matured between 22–24 March during 2002–03 and 2003–04, but maturity was earlier in the 2004–05 and 2005–06 seasons. At harvest, other crop parameters such as plant height, number of panicles, number of filled grains and 1000 grain weight were also measured.

TABLE 4. FIELD MANAGEMENT PRACTICES EMPLOYED FOR AMAN RICE, MEHERPUR, BANGLADESH (2002–05)

Management	2002	2003	2004	2005
Date of seeding on seedbed	July 02	July 04	July 11	July 04
Date of direct dry seeding	July 07	July 04	July 11	June 30
Date of transplanting	July 27	July 27	August 12	August 04
Weeding (no.)	2 for PTFS/CT, PTFR/CT and 3 for UPTB/D, UPDB/D and UPDF/D	3 for PTFS/CT, PTFR/CT and 5 for UPTB/D, UPDB/D and UPDF/D	3 for PTFS/CT, PTFR/CT and 5 for UPTB/D, UPDB/D and UPDF/D	3 for PTFS/CT, PTFR/CT and 6 for UPTB/D, UPDB/D and UPDF/D
Irrigation (no.)	5 for dry seeding and 6 for TP1	6 for dry seeding, 5 for TP	6 for dry seeding, 5 for TP	7 for dry seeding and 6 for TP
Fertilizer rate: N-P_2O_5–K_2O–S–Zn (kg/ha)	100–46–40–10–4	100–46–40–10–4	100–46–40–10–4	100–46–40–10–4
Basal: P_2O_5–K_2O–S–Zn (kg/ha)	46–60–10–4	46–60–10–4	46–60–10–4	46–60–10–4
N top dress (kg/ha)	25 kg at 18, 29, 44 and 60 DAE2; 25 kg at 15, 25, 35 and 45 DAE	25 kg at 20, 30, 43 and 56 DAE; 25 kg at 15, 24, 33 and 44 DAE	25 kg at 15, 30, 47 and 58 DAE; 25 kg at 15, 27, 36 and 46 DAE	25 kg at 15, 31, 46 and 59 DAE; 25 kg at 15, 28, 37 and 48 DAE
Date of flowering	Sept. 30 for direct seeding and Oct. 10	Sept. 30 for direct seeding and Oct. 09 for transplanting	Oct. 10 for direct seeding and Oct. 18 for TP	Oct. 01 for direct seeding and Oct. 11 for TP
Date of maturity	Oct. 31 for direct seeding and Nov. 07 for TP	Oct. 28 for direct seeding and Nov. 02 for TP	Nov. 07 for direct seeding and Nov. 14 for TP	Oct. 27 dry seeding and Nov. 05 for TP

Rice variety: BRRIdhan39; 1 TP = transplanted; 2 DAE = days after establishment

TABLE 5. FIELD MANAGEMENT PRACTICES EMPLOYED FOR WHEAT, MEHERPUR, BANGLADESH (2002–06)

Management	2002–03	2003–04	2004–05	2005–06
Date of seeding	Nov. 24, 2002	Nov. 22, 2003	Nov. 27, 2004	Nov. 27, 2005
Weeding	Herbicide+ 1 hand weeding	Herbicide+ 1 hand weeding	3	3
Irrigation (no.)	4	4	4	5
Fertilizer rate: N–P_2O_5–K_2O–S–Zn (kg/ha)	120–60–60–10–4	120–60–60–10–4	120–60–60–10–4	120–60–60–10–4
Basal: P_2O_5–K_2O–S–Zn (kg/ha)	58–60–60–10–4	58–60–60–10–4	58–60–60–10–4	58–60–60–10–4
N top dress (kg/ha)	34 kg at 19 DAS[1] and 28 kg at 35 DAS	34 kg at 21 DAS and 28 kg at 32 DAS	34 kg at 21 DAS and 28 kg at 32 DAS	34 kg at 19 DAS and 28 kg at 36 DAS
Date of flowering	Feb. 14, 2003	Feb. 10, 2004	Feb. 12, 2005	Feb. 09, 2006
Date of maturity	March 24, 2003	March 22, 2004	March 10, 2005	March 10, 2006

Wheat variety: Kanchan; [1] DAS = days after sowing

2.5. EVALUATION PARAMETERS

Crop productivity of the different treatments was compared in terms of rice equivalent yield (REY). REY was computed by converting the yield of wheat into a rice yield as follows [14]:

$$REY(t\ ha^{-1}) = \frac{Yield\ of\ wheat\ (t\ ha^{-1})\ x\ Market\ price\ kg^{-1}\ of\ wheat}{Market\ price\ kg^{-1}\ of\ rice}$$

Irrigation water received per treatment, water saving and average water productivity were estimated. Water productivity was expressed in terms of grain production per unit of irrigation water used (kg grain ha^{-1} mm^{-1}) and was calculated by dividing the yield of each crop with the amount of water applied under each treatment.

The following parameters were utilised to assess N use efficiency: Total (grain plus straw) N uptake by crop (rice and wheat). From the isotopic data, the isotopic parameter Nitrogen derived from the fertilizer (%Ndff), % ^{15}N fertilizer recovery in the crops (rice and wheat) and soil (0–45 cm depth), and ^{15}N fertilizer losses from the crop–soil system were determined.

2.6. STATISTICAL ANALYSIS

All the data were subjected to analysis of variance (ANOVA) and the treatment means statistical comparison was made using the Duncan Multiple Range Test (DMRT) at $P<0.05$.

3. RESULTS AND DISCUSSION

3.1. CROP PRODUCTIVITY

3.1.1. Rice productivity

Grain yields of rice obtained during four consecutive seasons (2002–05) are presented in Table 6. Rice grain yield in the different treatments differed significantly and the highest yield was found in the conventional treatment (PTFS/CT) in all the four seasons, followed by PTFR/CT.

TABLE 6. RICE GRAIN YIELD (t ha^{-1}), MEHERPUR, BANGLADESH, 2002–05

Treatment	2002	2003	2004	2005	Mean[a]
PTFS/CT	4.91 a	4.70 a	3.38 a	3.42 a	4.10
PTFR/CT	4.44 b	4.32 a	3.11 a	2.94 b	3.70 (10)
UPTB/D	4.77 ab	4.00 b	2.09 a	2.63 c	3.58 (13)
UPDB/D	4.57 ab	3.05 c	2.94 a	2.48 c	3.26 (20)
UPDF/D	3.89 c	3.15 c	2.16 b	2.08d	2.82 (31)

[a]Data in parentheses indicate per cent reduction in yield compared to the conventional practice (PTFS/CT).

Means within a column followed by a common letter are not significantly different (DMRT, $P<0.05$).

Compared with the 2002 season, irrespective of the crop establishment technique, rice grain yields decreased through all subsequent years. The overall yield reduction was 40% in 2005 compared to 2002. Grain yield was reduced in both UPTB/D and UPDB/D but direct seeding on zero tilled flat land (UPDF/D) always resulted in the lowest grain yields with a 31% reduction over the conventional transplanting (PTFS/CT). The lowest numbers of effective tillers (number of panicles) and filled grains found under flat and permanent raised beds may have contributed to these results (Table 7).

TABLE 7. STRAW YIELD, YIELD COMPONENTS AND PLANT HEIGHT OF RICE, MEHERPUR, BANGLADESH, IN 2005

Treatment	Straw yield ($t\ ha^{-1}$)	Panicles (m^{-2})	Filled grains (m^{-2})	1000–grain wt. (g)	Plant height (cm)
PTFS/CT	4.73 a	249 a	16930 a	22.6 a	95.5 a
PTFR/CT	3.94 b	234 ab	14730 b	22.3 a	96.0 a
UPTB/D	3.73 b	228 bc	14140 bc	22.3 a	91.7 a
UPDB/D	3.40 c	221 bc	13480 c	22.5 a	92.0 a
UPDF/D	2.74 d	211 c	13080 c	23.1 a	91.8 a

Means within a column followed by a common letter are not significantly different (DMRT, $P<0.05$).

The mean rice grain yields were 13 and 20% lower than that of the conventional transplanting (PTFS/CT) for UPTB/D and UPDB/D, respectively. The lower yields of rice in the non-puddled treatments (UPTB/D, UPDB/D and UPDF/D) may be attributed to an increased infestation of weeds, particularly *Cyperus rantandus* and *Cynodon dactylon.* Lower yields (37–50%) in the dry seeded rice beds than those of puddled transplanted rice (PTR) were found in India [15]. The authors suggested that severe weed and nematode build-up and unfavourable changes in the soil characteristics may have caused the yield reduction. Poor performance of direct seeded rice on beds was also reported by other authors [16, 17]. To increase yields of dry seeded rice, better weed control is an important crop management practice. Also, varieties with better adaptation to the particular local dry seeding conditions would need to be developed for the rice–wheat cropping systems. In this study, the rice variety (BRRIdhan39), which was developed for the conventional transplanting method, was used.

3.1.2. Wheat productivity

Grain yields of wheat are presented in Table 8. Wheat yields were significantly affected by the type of establishment technique in all years. In the first year (2002–03), zero tilled wheat (UPDF/D) showed a significantly lower grain yield (1.90 $t\ ha^{-1}$) while yields for PTFS/CT, PTFR/CT, UPTB/D and UPDB/D treatments were comparable and ranged from 2.57–2.62 $t\ ha^{-1}$. In the following year (2003–04), irrespective of crop establishment technique, the wheat yield increased but in the subsequent two years (2004–05 and 2005–06) the crop performed very poorly due to the abnormal weather conditions. The mean reduction in grain yield for these two years was 36 and 15% respectively, compared to the first two years.

TABLE 8. WHEAT GRAIN YIELD (t ha^{-1}), MEHERPUR, BANGLADESH, 2002–06

Treatment	2002–03	2003–04	2004–05	2005–06	Mean[a]
PTFS/CT	2.61 a	3.22 a	2.15 a	2.32 a	2.58
PTFR/CT	2.27 a	3.29 a	2.07 a	2.21 ab	2.46 (5)
UPTB/D	2.62 a	3.05 b	1.88 c	2.04 b	2.40 (7)
UPDB/D	2.57 a	3.21 a	1.98 b	2.07 bc	2.46 (5)
UPDF/D	1.90 b	3.20 a	1.90 b	1.82 c	2.20 (15)

[a]Data in parentheses indicate per cent reduction in yield compared to the conventional practice (PTFS/CT).Means within a column followed by a common letter are not significantly different (DMRT, $P<0.05$).

The reduction in wheat yields may likely be explained by the higher than average night temperatures, which prevailed during the grain filling stage. As a result the plants matured early having less spikes with many small or unfilled grains (Table 9). The average 1000-grain weight in 2005–06 (23.47 g) was reduced by 25 and 42%, respectively in 2004–05, which contributed to the lower grain yields. Unfavourable weather conditions during crop growth have been reported to cause low wheat yields [15].

TABLE 9. STRAW YIELD, YIELD COMPONENTS AND PLANT HEIGHT OF WHEAT, MEHERPUR, BANGLADESH, 2005–06

Treatment	Straw yield (t ha^{-1})	Panicles (m^{-2})	Filled grains (m^{-2})	1000–grain wt. (g)	Plant height (cm)
PTFS/CT	5.23 a	286 a	9790 a	23.40 a	100.5 a
PTFR/CT	4.67 b	274 a	9028 b	24.05 a	101.0 a
UPTB/D	3.87 cd	241 b	8124 c	24.23 a	101.8 a
UPDB/D	4.26 c	235 b	8225 c	24.10 a	102.3 a
UPDF/D	3.58 d	196 c	7051 d	24.08 a	97.8 b

Means within a column followed by a common letter are not significantly different (DMRT, $P<0.05$).

Over the whole duration of the experiment, the mean wheat yields on permanent raised beds (UPTB/D and UPDB/D) were lower than flatbed seeding (PTFS/CT and PTFR/CT) and yield was further reduced in the zero tilled plots (UPDF/D). The mean reduction was 5–7% for the raised beds, and 15% for zero tilled plots, compared to the flat bed planting (Table 8). The lower yields may be attributed to the reduced number of filled grain and a lower number of spikes m^{-2} (Table 9). The low spike density is due to the low soil moisture resulting in soil compaction and poor seedling emergence and seed damage by birds. Weed infestation was also a major problem for wheat management. Other authors have reported similarly lower yields of wheat under zero tillage compared to conventional or reduced tillage [18]. Higher wheat yields were obtained when planted on new beds compared to permanent beds and when planted on permanent beds where crop residues were retained [19, 20]. It was found in a long-term trial of permanent beds, that permanent raised beds with no residue retention exhibited declining productivity in a soybean–wheat system [21]. It was suggested that residue retention affected soil moisture and soil health, stressing the need to retain some crop residues when using permanent bed planting systems for better yields [21]. Further integrated work is required to assess the effect of permanent beds combined with selected crop management practices such as crop residue retention, varietal screening/testing and weed control methods.

3.2. WATER PRODUCTIVITY

Irrigation water management (water applied and estimated savings over flatbed treatment) and water productivity estimates in rice are presented in Table 10. The amount of irrigation water applied to UPTB/D and UPDB/D and UPDF/D was lower compared to PTFS/CT and PTFR/CT. On an average, irrigation water savings were around 24% for raised beds and 54% for zero tilled flat plots. High water saving in zero tilled plots may be attributed to reduced percolation as a result of soil compaction.

TABLE 10. IRRIGATION WATER APPLIED AND SAVED IN RICE, MEHERPUR, BANGLADESH, 2002–05

Treatment	Irrigation water applied (mm)					Water saved cf. flat (PTFS/CT) (%)					Mean water productivity
	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean	(kg grain ha^{-1} mm^{-1})
PTFS/CT	990	1080	1122	1280	1118	–	–	–	–	–	3.67
PTFR/CT	982	1058	1130	1255	1106	–	–	–	–	–	3.35
UPTB/D	770	810	864	957	850	22	25	23	25	24	4.21
UPDB/D	766	833	858	968	856	23	22	23	24	23	3.80
UPDF/D	417	480	510	655	516	58	56	54	49	54	5.47

Table 11 shows data on irrigation water management and the water productivity of wheat. UPTB/D and UPDB/D used 24% less irrigation water and UPDF/D used 14% less water when compared to PTFS/CT and PTFR/CT. Water productivity of rice and wheat for raised beds and zero tilled plots was also higher. Greater savings of irrigation water and higher water productivity for rice and wheat in rice–wheat systems using raised beds have been reported by many researchers [15, 22, 23, 24, 25, 26].

TABLE 11. IRRIGATION WATER RECEIVED AND SAVED IN WHEAT, MEHERPUR, BANGLADESH 2002–06

Treatment	Irrigation water applied (mm)					Water saved cf. flat (PTFC/CT) (%)					Mean water productivity (kg grain ha^{-1} mm^{-1})
	02/03	03/04	04/05	05/06	Mean	02/03	03/04	04/05	05/06	Mean	
PTFS/CT	378	418	375	448	405						6.37
PTFR/CT	374	420	366	462	406	–	–	–	–	–	6.06
UPTB/D	281	325	282	351	310	26	22	25	22	24	7.74
UPDB/D	285	315	278	368	312	25	25	26	18	24	7.88
UPDF/D	332	363	310	396	350	12	13	17	12	14	6.29

3.3. NITROGEN USE EFFICIENCY

3.3.1. Nitrogen use efficiency by rice

The N uptake by rice in biomass produced (grain and straw) varied from year to year (Table 12). Crop establishment techniques influenced the N uptake by rice (grain and straw) in each year. The mean total N uptake for three years (last column Table 12) ranged from 62 kg N ha^{-1} for the zero tilled flatbed treatment (UPDF/D) to 86 kg N ha^{-1} for the conventional puddled flatbed (PTFS/CT). The lowest N uptake is closely related to the lowest rice grain yield (Table 6). Crop N uptake is mainly affected by the crop growth and biomass produced rather than N concentration [27].

TABLE 12. N UPTAKE (kg ha^{-1}) BY RICE, MEHERPUR, BANGLADESH, IN 2002, 2004, 2005

Treatment	2002		2004		2005		Mean		
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Total
PTFS/CT	46.3 a	23.3 a	58.3 a	55.4 a	54.5 a	23.5 a	53	33	86
PTFR/CT	42.3 a	32.7 a	46.3 b	44.2 ab	48.7 b	19.7 ab	46	32	78
UPTB/D	61.7 a	32.8 a	54.7 a	46.0 ab	44.9 bc	17.6 b	52	31	83
UPDB/D	52.6 a	32.0 a	56.6 a	48.2 a	42.7 c	16.7 c	50	32	82
UPDF/D	48.5 a	20.7 a	36.7 b	34.7 b	35.8 d	12.9 c	40	22	62

Means within a column followed by a common letter are not significantly different (DMRT, $P<0.05$).

The isotopic data on % N derived from the fertilizer (% Ndff) in rice grain and straw for the years 2004 and 2005 are shown in Table 13. The % Ndff in grain and straw was significantly different for the various crop establishment techniques. In both years, % Ndff was higher for UPTB/D, UPDB/D and UPDF/D compared to conventional PTFS/CT. The mean % Ndff ranged from 32.2–44.5% in the grain and 32.5–41.3% in the straw. Higher % Ndff in the rice plants grown under the raised beds and zero tilled plots did not significantly influence the total ^{15}N fertilizer recovery by the rice due to the lower yields of these treatments.

TABLE 13. N DERIVED FROM FERTILIZER (Ndff, %) BY RICE, MEHERPUR, BANGLADESH, IN 2004 AND 2005

Treatment	2004		2005		Mean[a]	
	Grain	Straw	Grain	Straw	Grain	Straw
PTFS/CT	42.7 c	41.5 c	21.7 c	23.5 c	32.2	32.5 (–)
PTFR/CT	43.0 c	46.2 b	22.5 c	23.2 c	32.8	34.8 (–)
UPTB/D	51.3 b	50.2 a	28.1 b	26.7 bc	39.7 (23)	38.5 (18)
UPDB/D	53.1 a	48.4 ab	30.9 ab	29.3 b	42.0 (30)	38.8 (18)
UPDF/D	54.8 a	48.6 ab	34.1 a	34.1 a	44.5 (38)	41.3 (27)

[a]Data in parentheses indicate per cent increase in % Ndff compared to the conventional practice (PTFS/CT).
Means within a column followed by a common letter are not significantly different (DMRT, $P<0.05$).

The effect of crop establishment treatments on total recovery and estimated losses of ^{15}N fertilizer for the rice-soil system are shown in Table 14. Both the recovery of ^{15}N fertilizer (kg ha^{-1}) in the rice crop (grain and straw) and in the soil (0–45 cm depth) did not differ significantly. The mean recovery of ^{15}N fertilizer in the rice crop varied from 26.6–36.8 kg ha^{-1} and in the soil ranged from 12.8–14.9 kg ha^{-1}. The total ^{15}N fertilizer recovery in rice and soil ranged from 41–50% and consequently the estimated ^{15}N fertilizer losses (unaccounted for N) from the rice-soil system varied from 50–59% (Fig. 3).

TABLE 14. ^{15}N FERTILIZER RECOVERY (kg N ha^{-1}) IN THE RICE CROP AND THE SOIL, MEHERPUR, BANGLADESH, IN 2004 AND 2005

Treatment	2004		2005		Mean			2004	2005	Mean
	Grain	Straw	Grain	Straw	Grain	Straw	Total	Soil (0–45 cm)		
PTFS/CT	27.5	22.2	11.7	5.6	19.6	13.9	33.5	15.5	11.8	13.7
PTFR/CT	20.9	15.6	11.6	5.1	16.2	10.3	26.6	18.3	11.5	14.9
UPTB/D	27.5	23.6	12.3	4.7	19.9	14.1	34.0	17.4	10.7	14.1
UPDB/D	30.2	25.7	13.0	4.8	21.6	15.3	36.9	15.7	9.9	13.8
UPDF/D	21.5	17.7	12.0	4.4	16.7	11.1	27.8	17.8	9.9	13.9
CV (%)	23.6 ns	19.0 ns	9.8 ns	8.6 ns	–	–	–	11.5 ns	9.2 ns	–

CV, coefficient of variation; ns, not significant (*P*<0.05)

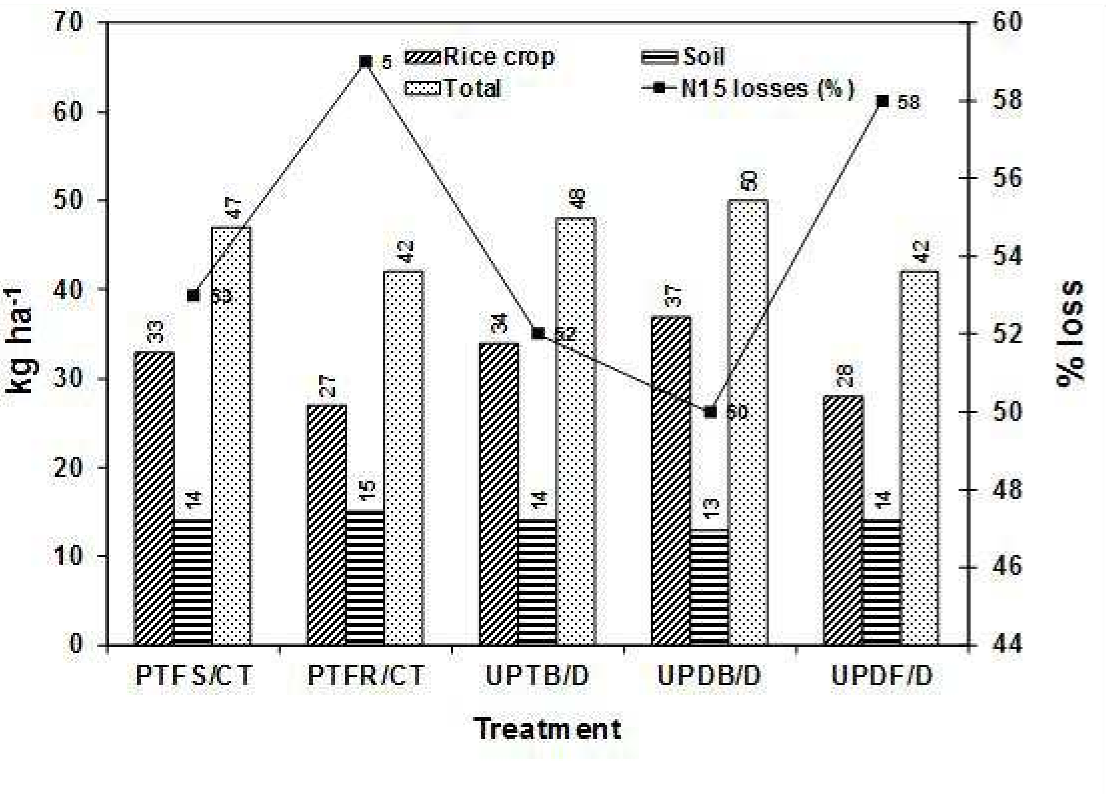

FIG. 3. ^{15}N fertilizer recovered in rice and soil and estimated losses from the rice–soil system.

3.3.2. Nitrogen use efficiency by wheat

The N uptake of wheat (grain and straw) for the seasons 2002–03 and 2005–06 is shown in Table 15. Crop establishment techniques significantly affected straw N uptake but no significant differences were found for grain N uptake. The total N uptake by the wheat crop in 2005–06 was relatively lower compared to that of the year 2002–03. The total N uptake means ranged from 57–73 kg ha^{-1}. A reduction in mean N uptake was found for wheat in treatments UPTB/D, UPDB/D and UPDF/D (12, 10 and 22% respectively) compared to PTFS/CT. The low total N uptake in these treatments was attributed to the lower dry matter yields. N uptake can be mainly affected by the crop growth and yield [27].

TABLE 15. N UPTAKE (kg ha^{-1}) AND N DERIVED FROM FERTILIZER (NDFF) IN THE WHEAT CROP, MEHERPUR, BANGLADESH, IN 2002–03 AND 2005–06

Treatment	2002–03			2005–06			Mean			Ndff (%)	
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw
PTFS/CT	52.9 a	22.2 a	75.1	47.4 a	24.2 a	71.6	50	23	73	34.1 ab	34.1 a
PTFR/CT	42.9 a	15.3 ab	58.2	42.1 a	18.5 b	60.7	43	17	60	37.3 a	35.6 a
UPTB/D	52.4 a	18.7 a	71.2	41.8 a	15.0 b	56.9	47	17	64	32.4 ab	30.7 a
UPDB/D	49.8 a	20.5 a	70.4	41.6 a	19.1 b	60.7	46	20	66	34.4 ab	30.6 a
UPDF/D	42.4 a	14.8 b	57.1	40.9 a	15.0 b	55.5	42	15	57	27.4 b	30.2 a

Means within a column followed by a common letter are not significantly different (DMRT, $P<0.05$).

The last column of Table 15 shows that N derived from fertilizer (% Ndff) for the 2005–06 season varied from 27.4–37.3% in the wheat grain and from 30.2–35.6% in wheat straw for the different treatments.

The effect of crop establishment treatments on total recovery and estimated losses of ^{15}N fertilizer for the wheat–soil system are shown in Table 16. The recovery of ^{15}N fertilizer in the wheat crop was very low and ranged from 16–24%. Reductions of 23 and 15% for UPTB/D and UPDB/D, respectively and of 34% in UPDF/D were found in comparison to the conventional PTFS/CT treatment (Table 16). This decrease may have resulted from the lower grain yields of the wheat in these treatments. The ^{15}N recovery from the soil ranged from 46.8–66.2% and was not influenced by crop establishment technique. A relatively large amount of applied fertilizer N remained in the soil after the wheat crop because the crop growth during the 2005–06 seasons was badly affected by unfavourable weather conditions. However, the estimated loss of ^{15}N fertilizer from the soil–wheat plant system ranged from 26–44%, being slightly lower than those reported above for rice (Fig. 3). Seepage and percolation rate are higher in the rainy season when rice is grown, which probably resulted in higher losses of N in this system. The maximum amount of ^{15}N was found in the upper layer and ^{15}N content in the soil decreased rapidly with depth in all treatments (data not shown). It was reported that the recovery of N from fertilizer depends on the requirements of the crop and climatic conditions. In this study, the wheat crop growth was badly affected by prevailing weather conditions [15].

TABLE 16. ^{15}N FERTILIZER RECOVERY (kg N ha^{-1}) IN THE WHEAT CROP AND THE SOIL AND ESTIMATED LOSSES, MEHERPUR, BANGLADESH, 2005–06

Treatment	Wheat			Soil	Loss (% of
	Grain	Straw	Total[a]	(0–45 cm)	applied N)
PTFS/CT	15.9 a	8.2 a	24.2	58.7 a	30
PTFR/CT	15.9 a	6.6 b	22.5	66.2 a	26
UPTB/D	13.7 a	4.6 c	18.4 (23)	57.0 a	37
UPDB/D	14.7 a	5.9 bc	20.6 (15)	46.8 a	44
UPDF/D	11.3 a	4.6 c	15.9 (34)	53.2 a	42

[a]Data in parenthesis indicate per cent reduction in ^{15}N recovery compared to the conventional PTFS/CT
Means within a column followed by a common letter are not significantly different (DMRT, $P<0.05$).

3.4. SYSTEM PRODUCTIVITY

A summary of the N use efficiency data of the rice–wheat systems studied is shown in Table 17. In total, 220 kg N ha^{-1} (100 kg for rice and 120 kg for wheat) as fertilizer N was applied to the rice–wheat system. Mean total N uptake for the system varied from 119–159 kg ha^{-1} (Table 17). The lowest N uptake was found in UPDF/D and the highest was in PTFS/CT. N uptake in UPTB/D and UPDB/D was 147 and 148 kg ha^{-1}, respectively. Total ^{15}N fertilizer recovery by both rice and wheat crops ranged from 44–58 kg ha^{-1}. Rice recovered 24 and 26% of applied fertilizer N in raised bed plantings UPTB/D and UPDB/D, respectively. The highest recovery was 26% in PTFS/CT and the lowest was 20% for UPDF/D. Low yields of both crops in the raised bed plantings and zero tillage treatments resulted in the low N uptake and ^{15}N fertilizer recovery.

Agronomic productivity (mean REY data of the four seasons) of the rice–wheat system is displayed in Fig. 4. Productivity declined in the UPTB/D, UPDB/D and UPDF/D treatments in the rice–wheat systems by 10 and 13% for UPTB/D and UPDB/D, respectively, and 24% in UPDF/D compared with PTFS/CT.

TABLE 17. MEAN TOTAL N UPTAKE, N DERIVED FROM FERTILIZER AND ^{15}N FERTILIZER RECOVERY IN THE RICE–WHEAT SYSTEM, MEHERPUR, BANGLADESH

Treatment	N uptake (kg ha^{-1})			N derived from fertilizer (%)				Recovery of fertilizer N (kg ha^{-1})		
	Rice	Wheat	Total	Rice		Wheat				
				Grain	Straw	Grain	Straw	Rice	Wheat	Total[a]
PTFS/CT	86	73	159	32.2	32.5	34.1	34.1	33.5	24.2	57.6 (26)
PTFR/CT	78	60	138	32.8	34.7	37.3	35.6	26.6	22.5	49.1 (22)
UPTB/D	83	64	147	39.7	38.5	32.4	30.7	34.0	18.6	52.6 (24)
UPDB/D	82	66	148	42.0	38.8	34.4	30.6	36.9	20.6	57.5 (26)
UPDF/D	62	57	119	44.5	41.3	27.4	30.2	27.8	15.9	43.6 (20)

[a]Data in parentheses indicate per cent of total fertilizer N applied to the rice–wheat system.

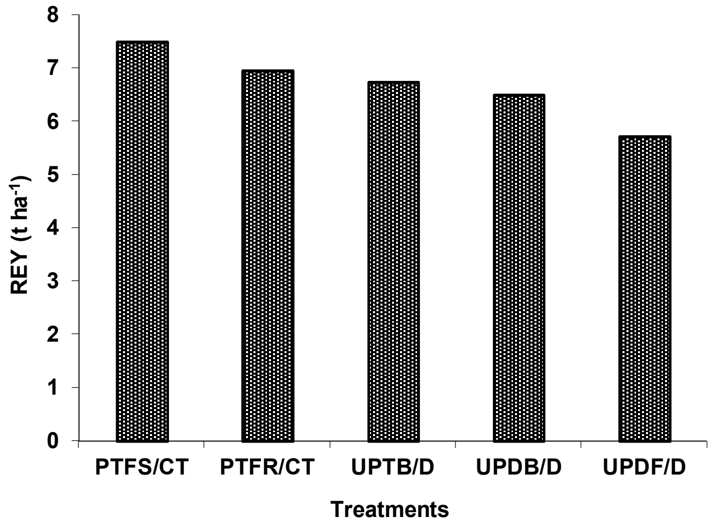

FIG. 4 Agronomic productivity of the rice–wheat system in Meherpur, Bangladesh.

4. CONCLUSIONS

Field experiments were conducted at Meherpur, Bangladesh during the period 2002–06 to make a comparative evaluation of the conventional (transplanting on puddled flatbed) and raised bed planting techniques on the productivity of a rice–wheat cropping system, in particular their effects on N fertilizer and water use efficiency.

Rice grain yields were reduced by up to 30% under direct seeding both on the flat and raised bed compared to the conventional practice. Wheat growth and grain yields were very variable over the years due to abnormal weather conditions during the winter period. Total agronomic productivity of the rice–wheat system decreased over time while raised bed planting and zero tillage resulted in yield reductions of 10–13 and 24%, respectively.

Raised bed planting showed some advantage over the conventional practice of transplanting of rice and seeding of wheat on pulverized soils in terms of water use efficiency. On average, raised bed planting and zero tillage saved 24 and 55% of irrigation water for the rice crop and 24 and 14% for wheat, respectively, compared to the conventional practice. The highest mean values of water productivity for rice were obtained for the treatments direct seeding and zero tillage on flat beds and transplanting in non-puddled raised beds, whereas the best treatments for wheat were seeding on permanent raised beds.

^{15}N fertilizer recovery by rice ranged from 27–37% with the crop establishment techniques. The total ^{15}N fertilizer recovery in rice and soil ranged from 41–50% and the estimated ^{15}N fertilizer losses (unaccounted for N) from the rice–soil system varied from 50–59%. ^{15}N fertilizer recovery by wheat was low and varied from 16–20% with the crop establishment techniques. The total ^{15}N fertilizer recovery in the wheat and soil ranged from 63–69% and the estimated ^{15}N fertilizer losses from the wheat–soil system varied from 31–37%. At the rice–wheat system level, ^{15}N fertilizer recovery by rice–wheat crops ranged from 20–26% in the various crop establishment techniques and tillage practices over the experimental period.

Further research adopting an integrated approach to crop, soil, water and nutrient management is needed before zero tillage and direct seeding technology can be successfully introduced and contribute to the development of sustainable rice–wheat cropping systems.

ACKNOWLEDGEMENTS

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CROP YIELDS AND ^{15}N RECOVERY OF RICE AND WHEAT GROWN SEQUENTIALLY WITH DIFFERENT CROP ESTABLISHMENT AND TILLAGE METHODS IN NEPAL

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Abstract

A field experiment was carried out in Ranighat, Parsa, Nepal from the 2002/03 to the 2005/06 cropping seasons to investigate the effect of crop establishment and tillage methods on nitrogen (N) and water use efficiency in a rice–wheat cropping system. The four cultivation treatments were as follows: (i) the conventional practice, i.e. rice transplanted into a flat puddled soil in summer followed by wheat seeded into well pulverized soil in winter (PTFS/CT) (ii) Transplanted rice into unpuddled beds followed by wheat sown with minimum tillage without disturbing the beds made for rice (UPTB/D) (iii) direct seeded rice in flat fields without puddling followed by wheat sown with minimum tillage (UPDF/D) and (iv) rice seeded into beds in paired rows without puddling, followed by wheat sown with minimum tillage into the bed (UPDB/D). ^{15}N labelled urea (5 atom % ^{15}N) was applied at 100 and 120 kg N ha^{-1} to rice and wheat, respectively, in micro-plots located within the main plots to assess fertilizer ^{15}N recovery in the crops, residual N in the soil and fertilizer N losses by mass balance. Averaged over four years, rice grain yields were significantly higher with conventional tillage and planting methods (PTFS/CT) compared to the new cultivation methods tested, and transplanted rice gave higher yields than direct seeded rice in both bed and flat systems. No differences in rice grain yields were observed between the bed and flat system within each planting method. In the first three years, yields were not affected by the treatments, but in the fourth rice crop yields were drastically reduced with direct seeding on the flat. Similarly, average wheat yields were highest with conventional cultivation. Both rice and wheat yields decreased through time. Mean N uptake by rice was significantly higher in PTFS/CT than in UPTB/D and UPDB/D treatments. Averaged over treatments and years, N uptake by rice was 107 kg N ha^{-1} that was similar to the N fertilizer application rate. Total N uptake by wheat was 68.4 kg N ha^{-1} of which 53.0 kg ha^{-1} was in grain and 15.4 kg ha^{-1} in straw. N uptake by wheat was higher in PTFS/CT than in UPTB/D and UPDB/D treatments. An average of 38.1% of the applied ^{15}N was recovered in rice plants and 16.6% in the soil. A significantly higher recovery of applied N in rice was observed in PTFS/CT (45.8%) compared to the other treatments (36.2%). The recovery of ^{15}N in the soil was not significantly different between treatments. Recovery of ^{15}N applied to wheat averaged 26.0% in the plant and 22.7% in the soil. In wheat a significantly higher recovery of 31.1% was observed in PTFS/CT compared to UPDF/D, but in soil a higher recovery was observed in UPTB/D compared to PTFS/CT and UPDF/D treatments. Water use efficiency by the wheat crop was again significantly higher at PTFS/CT (3.58 kg grain m^{-3} water) over the rest of the treatments (2.86 kg grain m^{-3} water).

1. INTRODUCTION

Nepal is a cereal–based agricultural country and rice–wheat is the predominant cropping system grown in the southernmost belt of the country. The plains, river basins and valleys are the major production areas of rice–wheat.During the 1991–1995 period some 520

000 ha were cultivated under the rice–wheat system with an average productivity of 3.61 t ha^{-1} year^{-1}. This cultivated land increased up to 550 000 ha with a productivity of 4.2 t ha^{-1} year^{-1} by the year 2000. Considering the potential productivity of the rice–wheat system to be 9.29 t ha^{-1} year^{-1}, this information would indicate that only 50% of the potential productivity was achieved. Increased production through expanding the cultivated land area is not a long-term viable option to meet the food requirements of the country. Future increases in agricultural production will have to come through increased productivity from the existing agricultural land. Maintenance of soil fertility, improving water and nutrient use efficiency and crop management practices and increased profitability are among the main factors to be considered to bridge the wide yield gap and sustain productivity of the intensive rice–wheat cropping system.

Rice in the summer wet season and wheat in the winter dry season are traditionally grown under puddled and well-pulverized soil conditions, respectively. Many researchers have reported that puddled rice culture adversely affects the subsequent wheat crop with respect to aeration, soil-water movement and root penetration. Various novel crop establishment and tillage or land preparation methods to address the problems associated with puddling and conventional wheat planting have been tested. It was reported that direct seeded rice in a rice–wheat system produced a significantly higher straw yield and similar grain yield than that of transplanted rice and increased the straw and grain yield of the subsequent wheat crop [1].

Nutrients, in particular nitrogen (N), have a significant effect on improving cereal crop yield and quality. Intensive use of fertilizers is not yet common in Nepalese agriculture except in some small areas due to several local factors such as accessibility, affordability, awareness, profitability, etc. Crop recoveries of less than 50% and estimated losses of 30–40% are commonly reported in fertilizer N use efficiency investigations. For instance it was reported that 38.5–40.2% of the applied N was recovered by the wheat crop in a Typic Haplustert soil [2], and the urea-N utilization by mustard ranged from 46–55% and losses were 27–39% in a Typic Ustochrept [3]. In a nitrogen balance study in a maize–millet cropping system in the mid-hills zone of Nepal, <25% of the applied fertilizer N was recovered in maize with only 3% recovered in the following millet crop [4]. Approximately 33% of the applied fertilizer was unaccounted for in the soil–crop system at the maize harvest.

Working in a system approach, the influence of new crop establishment and tillage methods on nitrogen and water use efficiency (NUE and WUE) and changes in soil physical conditions need to be better understood to increase productivity and sustainability of the rice–wheat cropping system. The objective of this study was, therefore, to evaluate the effects of selected crop establishment / tillage methods on rice and wheat yields, NUE, WUE and changes of soil physical conditions.

2. MATERIALS AND METHODS

2.1. EXPERIMENTAL SITE

The field experiment was run over four consecutive years (from 2002–03 to 2005–06 cropping cycles) under a rice–wheat system at the Agricultural Implement Research Centre, in Ranighat, Parsa, Nepal (Fig. 1). The soil at the experimental site was a silty loam and the main characteristics are given in Table 1.

2.2. CLIMATIC CONDITIONS

Mean monthly rainfall and air temperatures at the Parwanipur Agricultural Station, near to the experimental site are presented in Fig. 2a and Fig. 2b, respectively. The total annual rainfall during the experimental period ranged from 1524 to 2282 mm.

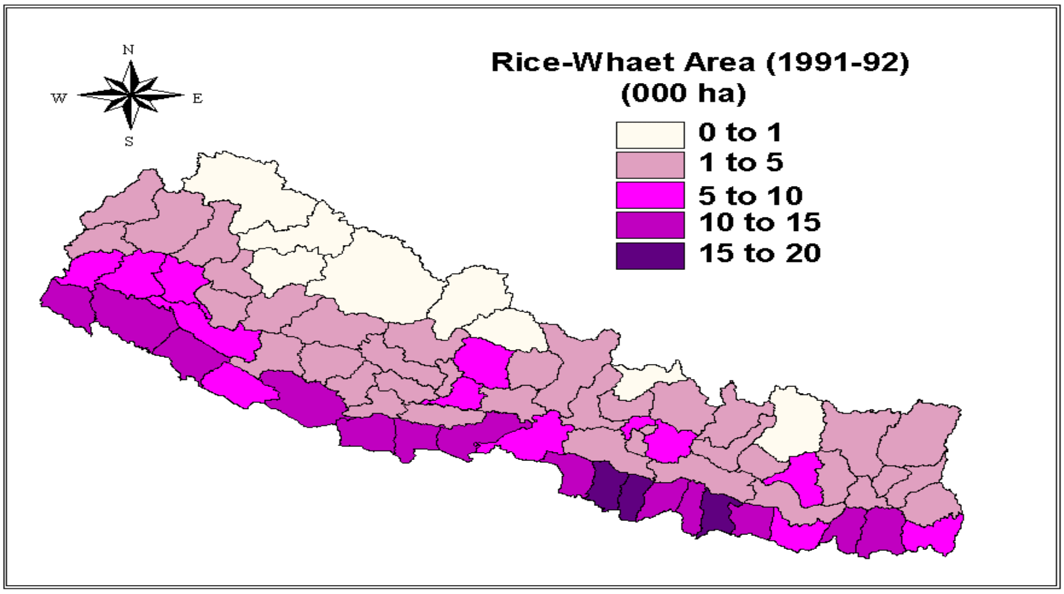

FIG. 1. Distribution of rice–wheat cropping belt areas in Nepal.

TABLE 1. CHARACTERISTICS OF THE SOIL (0–15 cm) OF THE EXPERIMENTAL SITE, RANIGHAT

Soil chemical characteristics		Soil physical characteristics	
pH	5.8	Bulk density (g cm^{-3})	1.6
Organic matter (g kg^{-1})	13.7	Sand (g kg^{-1})	345
Total N (g kg^{-1})	0.5	Silt (g kg^{-1})	490
P (mg kg^{-1})	10.4	Clay (g kg^{-1})	165
K (mg kg^{-1})	15.4	Moisture retention at field capacity (g kg^{-1})	89.5
		Moisture retention at wilting point (g kg^{-1})	60.4
		Hydraulic conductivity (mm hr^{-1})	0.234

2.3. EXPERIMENTAL DESIGN/TREATMENTS

The experimental treatments were four crop establishment / tillage methods. They were replicated four times in a Randomized Complete Block design (RCBD). A detailed description is presented in Table 2. In rice, within each main plot of 14 × 8 m, micro plots (1 × 0.8 × 0.4 m for the flat treatment and 1.2 × 0.67 × 0.55 m in bed planting) with tin sheet sides were laid down. The height of the box was 10 cm above the soil surface. In wheat, micro plots of the same size as in the rice crop were established at new sites within the main plots and these were delineated with iron pegs and ropes. ^{15}N-labelled urea (5 atom % ^{15}N) at the appropriate rate for the crop (Table 3) was applied to the micro plots and plants were grown to maturity.

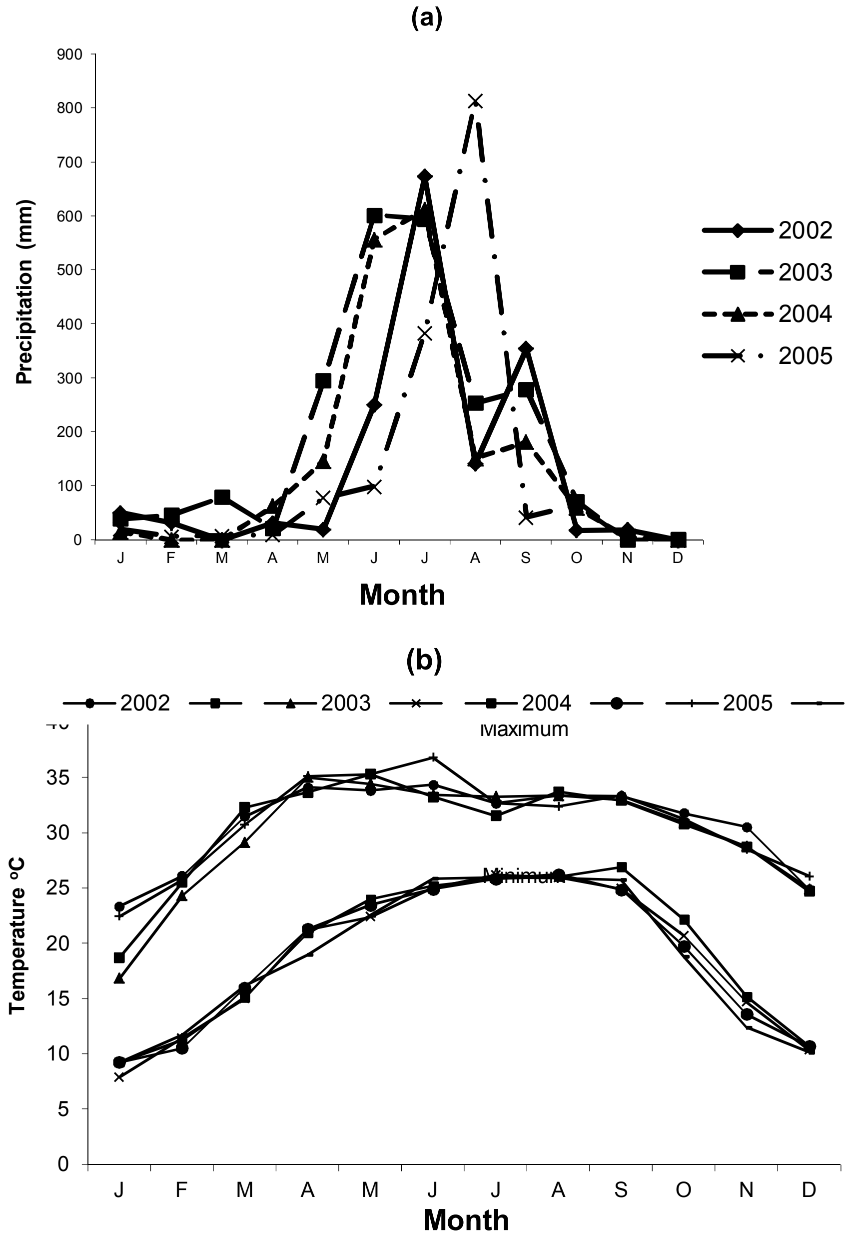

FIG. 2. Mean monthly rainfall (a) and maximum and minimum temperature (b) at Parwanipur weather station near to the experimental site.

2.4. FIELD/CROP MANAGEMENT

Rice and wheat crops were grown within the management treatments. Rice received a total of 100 kg N ha^{-1}, 46 kg P_2O_5 and 48 kg K_2O ha^{-1} and wheat 120 kg N, 60 kg P_2O_5 and 60 kg K_2O ha^{-1}. For rice the first split of 20 kg N, and all of the P and K were applied as a basal, and two more splits of 40 kg N were applied at tillering and panicle initiation. Wheat received the first split of 60 kg N ha^{-1} and all of the P and K as a basal, and two more splits of 30 kg N ha^{-1} as top dressings at tillering and jointing. The agronomic operations undertaken are presented in Table 3.

TABLE 2. DETAILS OF THE CROP ESTABLISHMENT TREATMENTS

Treatment	Rice crop	Wheat crop
PTFS/CT	Manual transplanting on puddled flat bed in row at 20 x 20 cm, a conventional method (PTFS).	Well pulverized soil with tractor ploughing, harrowing, planking, broad-casting fertilizer, and wheat seeds and then planking as farmers' practice (CT).
UPTB/D	Manual transplanting on unpuddled bed made with FIRBS at 65 cm from one bed to another bed. Paired rows on each bed at 20 x 20 cm. Bed width and height maintained were 37 and 15 cm, respectively (UPTB).	Seeding wheat on bed after rice crop without disturbing the previously made bed but reshaping the bed with FIRBS keeping two rows of wheat on each bed (D).
UPDF/D	Direct seeding of rice on unpuddled flat land previously ploughed and planked at 20 cm apart in row with tractor drawn seed drill (UPDF).	Wheat seeding with zero till drill without pre ploughing after rice in row, 20 cm apart (D).
UPDB/D	Direct seeding of rice on unpuddled raised bed prepared with FIRBS at 65 cm from one bed to another bed. Paired rice rows on each bed at 20 cm from one row to another row (UPDB).	Seeding wheat at 20 cm apart in row on the bed after reshaping the bed with FIRBS attached seed drill and maintaining two rows of wheat on each bed (D).

TABLE 3. AGRONOMIC OPERATIONS CARRIED OUT DURING FOUR CROPPING SEASONS 2002–05

Agronomic operation	2002		2003		2004		2005	
	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat
Variety	Sabitri	Vrikuti	Sabitri	Vrikuti	Sabitri	Vrikuti	Sabitri	Vrikuti
Seeding	24/5/02	23/11/02	27/5/03	23/11/03	2/6/04	28/11/04	9/6/05	12/11/05
T ' Planting	23/6/02	-	22/6/03	-	7/7/04	-	12/7/05	-
T ' dressing I	19/7/02	17/12/02	15/7/03	19/12/03	3/8/04	29/12/04	3/8/05	20/12/05
T ' dressing II	16/8/02	27/1/03	12/8/03	22/1/04	3/9/04	30/1/05	3/9/05	12/1/06
Harvesting	23/10/02	9/4/03	18/10/03	4/4/04	22/11/04	1/4/05	28/10/05	30/3/06
Soil sampling I	21/6/02	-	20/6 and 14/7	-	5/7and 4/8/04	-	10/7and 2/8/05	20/12/05
Soil sampling II	16/8/02	24/1/03	11/8/03	29/1/04	29/8/04	29/1/05	2/9/05	12/1/06
Soil sampling III	29/10/02	11/4/03	17/10/03	5/4/04	22/11/04	2/4/05	29/10/05	2/4/06
Seed rate, (kg ha^{-1})	40	120	40	120	40	120	40	120
N: P_2O_5: K_2O (kg ha^{-1})	100:46:48	120:60:60	100:46:48	120:60:60	100:60:60	120:60:60	100:46:48	120:60:60

2.5. PLANT AND SOIL SAMPLING AT HARVEST

At harvest time, grain and straw yields from the main plots where unlabelled urea was used were recorded.

Plant and grain samples of rice and wheat at harvest and post-harvest soil samples from three depths (0–15, 15–30, 30–45 cm) were collected from the microplots to determine % ^{15}N abundance. ^{15}N analyses in soil and plant samples were carried out at the IAEA Seibersdorf Laboratory, Austria.

2.6. SOIL SAMPLING AND DETERMINATION OF SOIL MINERAL NITROGEN (NO_3^--N AND NH_4^+-N)

Soil samples from four depths were taken at tillering in rice, jointing in wheat, and at harvest of each crop for mineral N determination. Composite soil samples from 0–15, 15–30, 30–60 and 60–90 cm depths of the experimental plots were taken with a tube auger and 120 ml of 2 M KCl was added to 40 g of fresh soil and immediately shaken for one hour in a reciprocating shaker. The extracted solutions were shipped to the laboratory and NO_3^--N was determined by colorimetry after reduction with cadmium (copperized cadmium reduction method) while NH_4^+-N was determined by semi micro distillation with MgO and titration of the distillate with standardized acid using bromocresol green and methyl red mixed indicator.

2.7. DETERMINATION OF SOIL BULK DENSITY AND POROSITY

A tube sampler of 21.9 mm internal diameter was used to take samples from each plot for measurement of bulk density and porosity. Duplicate samples were taken from the 0–15 cm depth in wheat but only 0–10 cm in rice. Samples were placed in aluminium foil and the moist soil weight recorded. They were then put in an oven at 105°C for 24 hours and the oven dry weight recorded. Bulk density, total porosity and air filled porosity were determined following standard procedures.

2.8. EVALUATION (NUE AND WUE) PARAMETERS

Recoveries of applied ^{15}N from soils and plants were calculated from the atom % ^{15}N excess in the samples as follows:

Recovery of applied fertilizer N in plant (%) = {(% ^{15}N excess in sample) / (% ^{15}N excess in fertilizer)} × N in sample (%) × yield (kg ha^{-1}) × 0.01 × {100 / N rate (kg ha^{-1})}. It is considered as index of nitrogen use efficiency (NUE).

Recovery of applied fertilizer N in soil (%) = {(% ^{15}N excess in sample) / (% ^{15}N excess in fertilizer)} × N in soil sample (%) × soil weight (kg ha^{-1}) × 0.01× {100 / N rate (kg ha^{-1})}.

Note: Weight of soil ha^{-1} was calculated using the bulk density of the soil layer.

Water use efficiency (WUE) in wheat was determined in terms of kg grain m^{-3} water used.

2.9. STATISTICAL ANALYSES

All data were subjected to analysis of variance. Comparisons of means were made using the Lsd test at $P<0.05$.

3. RESULTS AND DISCUSSION

3.1. RICE AND WHEAT GRAIN YIELDS

There were no significant differences for rice grain yield between treatments during the first three years but they were significantly different ($P<0.05$) in the fourth year. Significantly higher rice grain yields were recorded in PTFS/CT than in UPDF/D and UPDB/D in the fourth year. Averaged over the years, conventional puddling and transplanting of rice (PTFS/CT) gave a higher grain yield than UPDF/D and UPDB/D, but was similar to UPTB/D. Transplanted rice in both bed and flat systems gave higher yields than direct seeded rice, but yields were similar within the bed system (Fig. 3a).

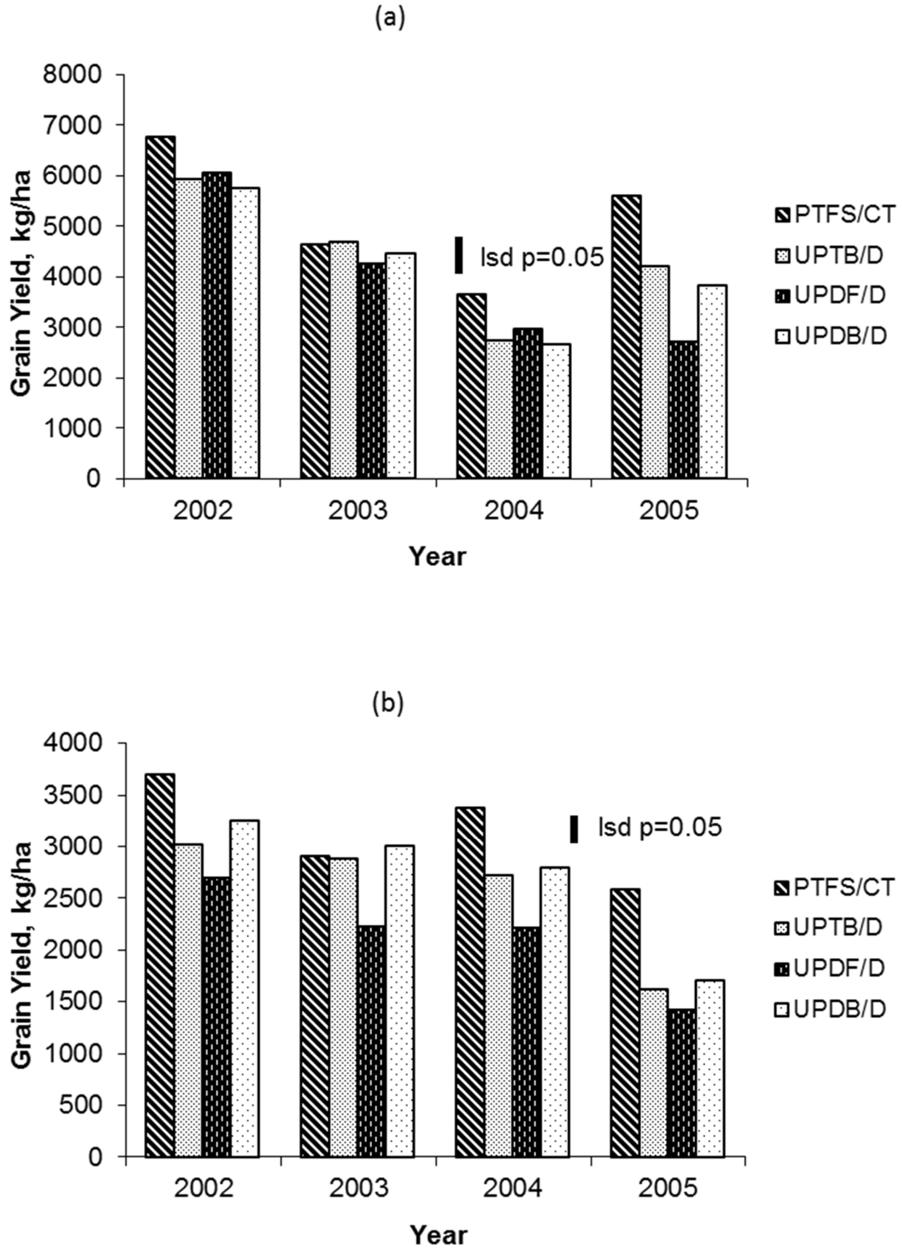

FIG. 3. Rice (a) and wheat (b) grain yields over four seasons

Significant differences between treatments in wheat grain yield were recorded in 2004 and 2005. The conventional tillage and planting method (PTFS/CT) gave significantly higher (P<0.01) grain yield than direct drilled or minimum tilled wheat on the flat (UPDF/D) in 2004 and over all three treatments in 2005. Average wheat grain yields over the four years were significantly higher in PTFS/CT than in the other treatments (Fig. 3b). Declines in grain yields of both rice and wheat were observed as the years proceeded, except rice in 2005 and wheat in 2004.

Average rice straw yields were not significantly different, but significantly higher yields was observed in UPDF/D in 2002 and in PTFS/CT in 2005 compared to the other treatments. Average wheat straw yields, averaged over the four years, as well as in 2003, were significantly higher ($P<0.01$) in PTFS/CT than in the other treatments (Table 4).

TABLE 4. GRAIN AND STRAW YIELDS OF RICE AND WHEAT (kg ha^{-1}) OVER FOUR SEASONS

Treatment	Rice grain					Wheat grain				
	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean
PTFS/CT	6767	4635	3643	5600	5155	3702	2916	3385	2590	3137
UPTB/D	5921	4696	2740	4212	4392	3018	2884	2725	1626	2563
UPDF/D	6053	4245	2950	2713	3990	2695	2232	2223	1423	2143
UPDB/D	5745	4445	2663	3811	4166	3251	3008	2800	1712	2693
Mean	6121	4505	2999	4080	4426	3167	2760	2778	1838	2634
Lsd	–	–	–	1656	865	–	584	–	372	307
Treatment	Rice straw					Wheat straw				
	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean
PTFS/CT	6909	8317	4825	7112	6792	3242	3951	2970	2610	3193
UPTB/D	7257	7627	3078	4351	5578	2758	3036	2459	2294	2637
UPDF/D	10550	7160	4123	3684	6379	2321	2455	1988	1730	2124
UPDB/D	7813	6569	4061	4180	5656	2835	3231	2514	1909	2622
Mean	8132	7417	4022	4832	6101	2789	3168	2483	2136	2644
Lsd	2258			854	–	–	685	–	–	304

Lsd, least significant difference ($P<0.05$)

Traditionally in Nepal, rice is transplanted into puddled soil. It was shown that direct seeded rice produced grain yield as good as that of transplanted rice, and wheat grain yield grown after direct seeded rice was significantly higher than after transplanted rice [1]. Research carried out elsewhere in Nepal, indicated that direct seeded rice sown on the flat out yielded transplanted rice both in terms of grain and straw yields, but in beds the rice grain yields were almost equal [5]. In this experiment, based on the average of the four years, direct seeded rice on the flat (UPDF) as well as direct seeded rice on beds (UPDB) gave a lower yield than transplanted puddled rice in flat (PTFS) and unpuddled transplanted rice on beds (UPTB). Direct seeding of rice in flats or in beds needs better weather information where there is no assured irrigation. In Nepal, farmers have limited access to a reliable weather forecasting system and hence they prefer rice transplanting although it is a labour intensive practice in nature. In this experiment the succeeding wheat yields when planted with minimum tillage in the flat (UPDF/D) followed by direct seeding of rice in the flat were found to be the lowest, and this trend was maintained over all four years reaching significant levels in 2003 and 2005. These results suggested that continuous rice–wheat cropping without any tillage operations on the same piece of land is not sustainable, and in the long term would result in soil degradation, increased pest and disease incidence and poor yields. These issues demand more investigations on the rice–wheat cropping systems by adopting an integrated approach to crop, soil, water and nutrient management.

3.2. TOTAL NITROGEN UPTAKE BY RICE AND WHEAT

Total N uptake by rice was significantly higher in the conventional planting treatment (PTFS/CT) than UPTB/D and UPDB/D with the average varying from 97 to 122 kg N ha^{-1} over the years (Table 5). Mean grain N uptake was significantly higher in PTFS/CT than UPDF/D and UPDB/D and mean straw N was significantly higher in UPDF/D than UPDF/D and UPDB/D.

TABLE 5. N UPTAKE (kg ha^{-1}) BY RICE AND WHEAT CROPS OVER FOUR SEASONS

Treatment	Rice grain					Rice straw					Rice plant total				
	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean
PTFS/CT	113.9	66.6	50.4	81.0	78.0	41.8	58.8	30.5	45.2	44.1	155.7	125.4	80.9	126.2	122.0
UPTB/D	102.7	69.5	39.5	59.5	67.8	47.1	43.5	18.3	29.0	34.5	149.8	113.0	57.9	88.5	102.3
UPDF/D	98.2	55.2	49.0	34.7	59.3	83.3	47.8	31.8	25.5	47.1	181.4	103.0	80.8	60.2	106.3
UPDB/D	86.0	62.1	38.0	52.5	59.6	55.4	34.6	31.5	27.7	37.3	141.4	96.8	69.5	80.2	97.0
Mean	100.2	63.4	44.2	56.9	66.2	56.9	46.2	28.0	31.8	40.7	157.1	109.5	72.3	88.8	106.9
Lsd	–	–	–	28.6	15.0	11.4	–	–	5.5	7.5	–	18.3	–	29.2	17.6
Treatment	**Wheat grain**					**Wheat straw**					**Wheat plant total**				
	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean
PTFS/CT	78.5	64.0	56.8	38.9	59.5	15.1	24.3	14.5	15.3	17.3	93.7	88.3	71.3	54.2	76.9
UPTB/D	69.6	59.9	52.6	24.6	51.7	14.3	20.3	13.8	13.8	15.6	83.9	80.2	66.4	38.4	67.3
UPDF/D	63.0	46.8	43.1	23.1	44.0	13.1	14.4	11.5	11.1	12.5	76.1	61.2	54.6	34.2	56.6
UPDB/D	72.9	67.4	57.5	28.7	56.6	15.1	24.8	14.6	10.7	16.3	87.9	92.2	72.2	39.4	72.9
Mean	71.0	59.5	52.5	28.8	53.0	14.4	21.0	13.6	12.7	15.4	85.4	80.5	66.1	41.6	68.4
Lsd	–	8.8	–	7.5	8.0	–	2.4	–	–	2.5	–	7.5	–	6.8	9.3

Lsd, least significant difference (*P*<0.05)

Total N uptake in wheat was higher in conventionally planted wheat, (PTFS/CT, 76.9 kg ha^{-1}) than UPDF/D. Grain and straw N uptake was also higher in PTFS/CT than UPDF/D. The average N uptake of the treatments and years was 53.0 kg N ha^{-1} in grain and 15.4 kg N

ha^{-1} in straw (Table 5). This was most likely due to a lower biomass production of wheat and a higher N application rate compared to rice in all four cropping cycles.

3.3. RECOVERY OF UREA APPLIED TO RICE AND WHEAT

Mean (four year), N derived from fertilizer (Ndff , %) values in rice grain and straw were significantly different between treatments ranging from 19.4 to 28.4% in grain, and from 13.1 to 17.4% in straw. Highest %Ndff values were found with conventionally transplanted, puddled rice (PTFS/CT), which was significantly higher than the other three treatments (Table 6).

TABLE 6. N DERIVED FROM FERTILIZER (Ndff, %) IN GRAIN AND STRAW OF RICE OVER FOUR SEASONS

Treatment	Grain					Straw				
	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean
PTFS/CT	32.9	26.0	24.4	30.4	28.4	14.6	22.0	13.0	20.1	17.4
UPTB/D	28.3	23.9	18.2	23.8	23.5	14.8	17.3	7.3	13.1	13.1
UPDF/D	29.0	20.5	16.0	12.3	19.4	23.1	17.4	10.3	10.1	15.2
UPDB/D	28.9	23.7	16.6	19.5	22.2	15.0	15.5	10.9	11.2	13.1
Mean	29.8	23.5	18.8	21.5	23.4	16.9	18.0	10.4	13.6	14.7
Lsd					5.5					4.9

Lsd, least significant difference ($P<0.05$)

In wheat, % Ndff in both grain and straw was significantly ($P<0.01$) different between treatments. In grain, it ranged from 18.2 to 29.8% and in straw from 4.8 to 7.5%. The highest values were also observed for the PTFS/CT treatment which was significantly higher than UPDF/D (Table 7).

TABLE 7. N DERIVED FROM FERTILIZER (Ndff, %) IN GRAIN AND STRAW OF WHEAT OVER FOUR SEASONS

Treatment	Grain					Straw				
	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean
PTFS/CT	33.4	28.2	29.4	28.1	29.8	6.4	10.4	6.0	7.2	7.5
UPTB/D	27.8	27.7	25.5	16.5	24.4	5.8	7.3	5.3	7.3	6.4
UPDF/D	24.0	18.9	17.8	12.1	18.2	6.2	4.8	3.7	4.5	4.8
UPDB/D	32.4	30.4	28.5	16.9	27.1	6.0	9.6	5.9	5.9	6.9
Mean	29.4	26.3	25.3	18.4	24.9	6.1	8.0	5.2	6.3	6.4
Lsd					3.8					1.2

Lsd, least significant difference ($P<0.05$)

Mean values of fertilizer ^{15}N recovery in rice ranged from 35.4–45.8%. The treatment means were only significantly different in 2005, but not in other years (Table 8). The mean recovery of ^{15}N labelled urea over the years in grain + straw was significantly higher in PTFS/CT than in other treatments (Fig. 4). Mean recovery of ^{15}N fertilizer from soil at rice harvest ranged from 15.1–18.5% (Table 8) and was not significantly different between treatments in any year.

TABLE 8. RECOVERY OF APPLIED ^{15}N FERTILIZER (%) FROM SOIL (0–15 cm) AND PLANTS IN RICE AND WHEAT CROPS OVER FOUR SEASONS

Treatment	Rice soil					Wheat soil				
	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean
PTFS/CT	14.4	14.5	22.4	22.6	18.5	14.0	19.5	16.1	21.4	17.8
UPTB/D	12.8	12.9	20.5	18.5	16.2	21.5	24.7	25.1	44.9	29.1
UPDF/D	11.5	11.5	23.4	20.6	16.8	15.0	11.0	12.6	31.2	17.4
UPDB/D	9.2	9.2	24.0	18.1	15.1	15.3	24.1	24.2	42.8	26.6
Mean	12.0	12.0	22.6	20.0	16.6	16.4	19.8	19.5	35.1	22.7
Lsd					ns					6.8
Treatment	Rice plant					Wheat plant				
	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean
PTFS/CT	47.3	48.1	37.4	50.5	45.8	33.1	32.2	29.5	29.4	31.1
UPTB/D	43.0	41.2	25.5	36.9	36.7	28.0	29.1	25.6	19.9	25.7
UPDF/D	52.1	37.8	32.2	22.4	36.1	25.2	19.7	17.9	13.9	19.2
UPDB/D	43.9	39.3	27.6	30.6	35.4	32.0	33.4	28.7	19.0	28.3
Mean	46.6	41.6	30.6	35.1	38.5	29.6	28.6	25.4	20.5	26.0
Lsd					7.0					3.9
Treatment	Rice total recovery (plant + soil)					Wheat total recovery (plant + soil)				
	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean
PTFS/CT	61.8	62.6	59.8	73.1	64.3	47.2	51.8	45.6	50.8	48.8
UPTB/D	55.9	54.0	46.0	55.4	52.8	49.5	53.9	50.8	64.8	54.7
UPDF/D	63.6	49.4	49.7	43.0	51.4	40.2	30.7	30.5	45.1	36.6
UPDB/D	53.1	48.5	51.5	48.8	50.5	47.3	57.5	52.8	61.8	54.9
Mean	56.8	52.8	51.8	55.1	54.8	46.0	48.5	44.9	55.7	48.8
Lsd					8.6					7.9

Lsd, least significant difference (P<0.05); ns, not significant

Mean recovery of applied ^{15}N fertilizer in wheat was significantly higher in PTFS/CT (31.1%) than in UPDF/D (19.2%). A similar trend was observed in 2004 and 2005 (Fig. 4 and Table 8). A higher recovery of applied ^{15}N fertilizer was found in grain and straw in PTFS/CT than UPDF/D (data not shown). At the wheat harvest, significantly higher ^{15}N fertilizer recoveries were observed in the soil in beds (UPTB/D and UPDB/D) than in flats within the same method of rice planting, which might be due to higher aeration in the bed. Mean values of the total recovery (soil + plant) of the applied ^{15}N fertilizer in wheat ranged from 36.6% in UPDF/D to 54.9% in UPDB/D, but in rice the total recovery varied from 50.5% in UPDB/D to 64.3% in PTFS/CT (Table 8). These results would indicate that the conventionally transplanted rice in puddled soil is a better choice for rice cropping in terms of fertilizer N recovery.

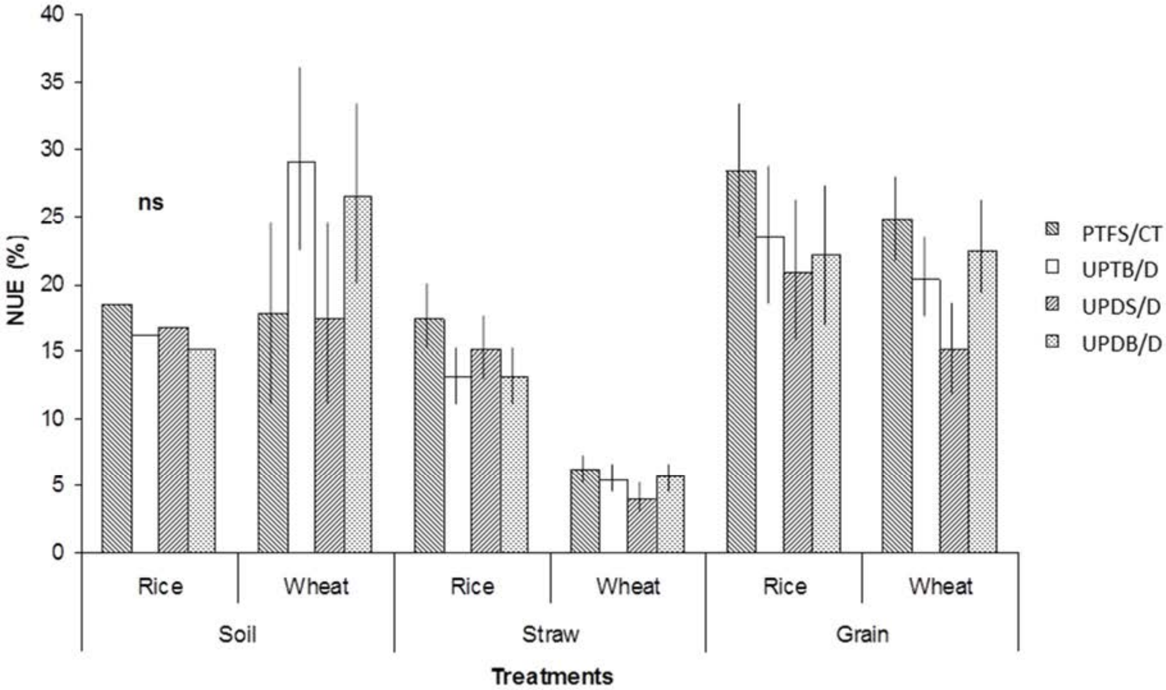

FIG. 4: Four year mean N use efficiency (%) in rice and wheat crops. Lsd bars P<0.05.

Recovery of applied N by the crop depends on a number of factors and their interactions, including crop cultivar, soil biophysical conditions, and crop management practices. In this experiment, recovery data of the applied ^{15}N fertilizer by wheat are close to the values reported elsewhere [2]. The higher recoveries observed in rice than those of wheat may be due to the lower N rates used in the previous crop. The N use efficiency in rice was not improved with the new tillage and crop establishment techniques when compared to conventional practices. However, in the wheat crop, a small improvement was observed with minimum tilled wheat sown into beds (UPDB/D) followed by direct seeded rice in beds.

Averaged over treatments and years, 16.6% of the total fertilizer N remained in the topsoil (0–15 cm) after the rice crop and 22.7% after wheat. Residual fertilizer N in the lower soil layers was negligible and not considered in the balance (data not shown). This indicated that downward movement of applied fertilizer N was not extensive under the Parsa experimental conditions where the mean annual rainfall ranges from 1524–2282 mm. In contrast, a rapid transformation and downward movement of N under maize/millet cropping was reported in a levelled bench terrace system of the mid hills of Nepal [4], where about 60% of the ^{15}N-labelled fertilizer recovered in the soil at harvest was found below 20 cm.

3.4. WATER USE EFFICIENCY

Annual and mean water use efficiency (WUE) data for wheat over four seasons are shown in Table 9. WUE treatment means of the four years were significantly different. Conventionally grown wheat (PTFS/CT) had higher water use efficiency over the other three treatments, and the lowest WUE was observed in the UPDF/D treatment (Table 9).

TABLE 9. ANNUAL AND MEAN WATER USE EFFICIENCY IN WHEAT OVER FOUR SEASONS

Treatment	Water use efficiency (kg grain m^{-3} water)				
	2002	2003	2004	2005	Mean
PTFS/CT	1.77	4.90	4.18	3.45	3.58
UPTB/D	1.42	4.74	3.43	2.24	2.96
UPDF/D	1.30	3.81	2.89	2.37	2.59
UPDB/D	1.50	4.68	3.51	2.43	3.03
Mean	1.50	4.53	3.50	2.62	3.04
Lsd ($P<0.05$)					0.54

4. CONCLUSIONS

Field experiments were conducted over four years at the Agricultural Implement Research Centre, in Ranighat, Parsa, Nepal to investigate the effects of new crop establishment / tillage methods on the crop yields, NUE and WUE of the rice–wheat cropping system.

The new crop establishment methods such as direct seeded rice on the flat or in beds (UPDF or UPDB), and direct drilling of wheat (D) without tillage on the flat or in beds, in the rice–wheat system were found to be less productive, and less N efficient compared to conventional methods of transplanted rice on the puddled flat followed by tilled pulverized soil for wheat (PTFS/CT).

Rice transplanted into a puddled field followed by wheat seeded into pulverized soil (PTFS/CT) produced the highest rice and wheat yield of 8.3 t ha^{-1} y^{-1}. The lowest yield of 6.1 t ha^{-1} y^{-1} was recorded with direct seeding of rice followed by wheat with minimum tillage on flats (UPDF/D). Other options, such as puddled transplanted rice in flats (PTFS) with minimum till drilled wheat grown for, say 4–5 cropping cycles, and then changing to normal ploughing of wheat should be evaluated.

An average of 38.1% of the applied ^{15}N was recovered in rice plants and 16.6% in the soil. A significantly higher recovery of applied N in rice was observed in PTFS/CT (45.8%) compared to the other treatments (36.2%). The recovery of ^{15}N in the soil was not significantly different between treatments. Recovery of ^{15}N applied to wheat averaged 26.0% in the plant and 22.7% in the soil. In wheat a significantly higher recovery of 31.1% was observed in PTFS/CT compared to UPDF/D but in soil a higher recovery was observed in UPTB/D compared to PTFS/CT and UPDF/D. Water use efficiency by wheat in PTFS/CT

(3.58 kg grain m^{-3} water) was significantly higher than the rest of the treatments (2.86 kg grain m^{-3} water).

These results suggested that continuous rice–wheat cropping without any tillage operations on the same piece of land is not sustainable, and in the long term would result in soil degradation, increased incidence of pests and diseases and poor yields. These issues demand more investigations on the sustainability of rice–wheat cropping systems adopting an integrated approach to crop, soil, water and nutrient management.

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INTEGRATED SOIL, WATER AND NITROGEN MANAGEMENT FOR SUSTAINABLE RICE–WHEAT CROPPING SYSTEM IN PAKISTAN

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Abstract

The area under the rice–wheat (R–W) cropping system in Pakistan is about 2.2 Mha and despite its great importance as staple foods for the local population, the productivity of the system is poor due to several constraints. Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) are normally grown in sequence on the same land in the same year. Field experiments with rice and wheat were conducted during four years on a Typic Halorthid soil at Lahore, in the alluvial plain of Punjab, Pakistan to assess nitrogen use efficiency and water productivity under both traditional and emerging crop establishment methods (raised beds, unpuddled soil, direct seeding). The climate in this region is semiarid. The experimental design was a randomized complete block design with five crop establishment methods as treatments and four replications. One micro-plot was laid down in each main plot to apply ^{15}N labelled urea (5 atom % ^{15}N). Both wheat and rice received a uniform application of 120 kg N ha^{-1} as urea, 30 kg P ha^{-1} as triple super phosphate, 50 kg K ha^{-1} as potassium sulphate and 5 kg Zn ha^{-1} as zinc sulphate. Pooled data of wheat grown in 2002–03, 2004–05 and 2005–06 showed that the highest wheat grain yield (3.89 t ha^{-1}) was produced with conventional flatbed sowing (well pulverised soil) followed by raised bed sowing (3.79–3.82 t ha^{-1}), whereas the lowest yield (3.45 t ha^{-1}) was obtained in flat bed sowing with zero till rice in sequence. The highest rice paddy yield (4.15 t ha^{-1}) was achieved with conventional flooded transplanted rice at 20 × 20 cm spacing and the lowest paddy yield (3.57 t ha^{-1}) was recorded with direct seeding of rice in zero tilled soil. Total N uptake in wheat was maximum (117 kg ha^{-1}) with conventional flatbed sowing and it was lowest with zero tilled soil. The highest total N uptake by rice (106 kg ha^{-1}) was recorded with conventional flooded transplanted rice at 20 × 20 cm spacing and the lowest (89 kg ha^{-1}) with direct seeded rice in zero tilled soil. Percentages of wheat N derived from labelled fertilizer (%Ndff) in were higher than those in rice, with values ranging from 29 to 34% in wheat and 18 to 25% in rice. Significantly lower %Ndff was measured in wheat with zero tilled soil than all other treatments. A similar trend was found in the rice crop. In both crops the highest fertilizer ^{15}N recovery was achieved with the conventional method of sowing / transplanting and it was the lowest where the crop was grown on the flat bed into zero tilled soil. Fertilizer ^{15}N recovery by rice ranged from 17 to 28%, and in wheat from 28 to 38%. The percentage of ^{15}N recovered from soil (0–45 cm) after rice harvest ranged from 21 to 34% and from 26 to 32% after wheat harvest. The estimated mean ^{15}N fertilizer losses were higher in rice (46.4%) than in wheat (36.7%). In both crops, ^{15}N losses were highest where the crops were grown on flat beds with zero tillage. Mean irrigation water productivity for wheat ranged from 10.5 to 12.9 kg grain ha^{-1} mm^{-1} water. Water productivity was higher (12.9 kg grain ha^{-1} mm^{-1} water) in raised beds as compared to conventional flatbed sowing of wheat (11.1 kg grain ha^{-1} mm^{-1}). Water productivity for rice ranged from 1.84 to 2.30 kg grain ha^{-1} mm^{-1} water. The highest water productivity values (2.3 kg grain ha^{-1} mm^{-1} water) were obtained with rice on raised beds either direct seeded or transplanted. In both crops, estimated water productivity was higher in raised beds than in flat beds.

1. INTRODUCTION

Rice–wheat (R–W) system occupies about 13.6 Mha in the Indo-Gangetic Plains, with 10.3 Mha in India, 2.2 Mha in Pakistan, 0.6 Mha in Nepal and 0.5 Mha in Bangladesh [1, 2, 3]. Despite the central position of rice and wheat as the main staple food crops in Pakistan, the productivity of the R–W system is poor, with an average yield of 2 t ha^{-1} and 2.2 t ha^{-1} for rice and wheat, respectively. Rice and wheat are cereal crops grown in sequence on the same piece of land. The poor wheat yield is attributed to the deteriorated soil structure resulting from the soil pulverization or puddling made for rice. Soil puddling is a practice generally considered beneficial for flooded lowland rice, but it destroys soil aggregates and creates a hardpan. Puddling for rice also induces high bulk density, high soil strength and low permeability in subsurface layers [4, 5, 6], which can restrict root development and water and nutrient use from the soil profile for wheat sown after rice [7, 8]. Further, after the rice harvest, when the land is prepared for wheat sowing, big clods are formed, which have an effect on seed germination and establishment of wheat because of poor soil to seed contact. However, the impact of puddling for rice on the performance of wheat after rice has been found to be variable across sites and years [9].

In Pakistan, as in most countries of Asia, conventional wheat is sown on a flatbed after rice. Although zero tillage has not yet been widely adopted in Pakistan, it can help farmers to sow wheat in a single tillage operation after rice harvest and could also help to save irrigation water. Wheat planting on raised beds is another promising technique that can reduce production costs when beds are permanent. There is a need for better R–W production technologies, which must be resource use efficient (labour, water, energy and N fertilizer) to contribute to sustainable high productivity of both rice and wheat. Direct seeding on unpuddled soil and raised beds has been proposed as an alternative rice establishment method, primarily to cope with labour shortages at transplanting time. Adoption of these practices would help to improve soil structure in the rice–based cropping system.

Water shortage is a major constraint to sustaining and increasing the productivity of R–W systems. Substantial increases in rice and wheat yields have been achieved largely due to the use of improved varieties and better management of water, nutrients, weeds, pests and diseases [10, 11, 12, 13], resulting in higher irrigation and total water productivity of R–W systems in Asia. Low soil N availability is the most important yield limiting factor in the R–W system in Pakistan. Further, fertilizer N use efficiency is often low in these crops. Thus, increasing the efficient use of N fertilizer and saving water are issues of prime concern in this system.

Current research is in progress to develop new crop establishment techniques that have the potential to increase yields and water productivity. The effects of alternative planting techniques such as bed transplanting; direct seeding and parachute planting methods are being investigated for rice, and raised bed planting and zero tillage for wheat after rice. However, the influence of these alternative and emerging crop establishment techniques on N use efficiency (NUE), N losses at the field scale and water productivity and water savings at the system level are not yet known.

Field experiments were therefore conducted during the period 2002–05 with the overall objective of studying the effects of new crop establishment methods on the productivity and sustainability of R–W cropping system in Pakistan. The specific objective was to assess water productivity and nitrogen use efficiency under both traditional and emerging crop establishment methods (raised beds, non-puddled soil, direct seeding). ^{15}N labelled urea was utilised to investigate the effect of these new crop establishment techniques on fertilizer N uptake by the crop, N fertilizer recovery in soil and N losses by mass balance.

2. MATERIALS AND METHODS

2.1. EXPERIMENTAL SITE

The field experiments were conducted during the period 2002–06 by growing rice and wheat in sequence at Lahore, Rice Research Institute, Kala Shah Kaku, Punjab province, Pakistan.

The soil was a Typic Halorthid, Dungi soil series. Selected initial soil fertility characteristics of the experimental site were: textural class, clay loam; pH (1:1), 8.1; EC (1:1), 0.42 dS m^{-1}; total N, 1.18 g kg^{-1}; organic matter, 9.6 g kg^{-1} ; free $CaCO_3$, 26 g kg^{-1}. AB–DTPA extractable nutrients were (mg kg^{-1} soil): NO_3–N, 6.7; P, 2.34; K, 75; Zn, 0.52; Fe, 4.3; Cu; 6.8; Mn, 1.16. The soil was deficient in NO_3^--N (critical value for NO_3^--N is 10 mg kg^{-1} of soil). Soils having <3 mg AB-DTPA P kg^{-1} are considered deficient for crop growth, and thus the soil was also deficient in P. As 60–120 mg K kg^{-1} is rated as medium, the field soil was moderate in K fertility. Zinc was deficient in the soil, whereas Fe, Cu and Mn were not deficient [14].

2.2. CLIMATIC DATA

The climate of the area is semiarid and subtropical. The mean minimum and maximum temperatures during the rice season were 24.4 and 33.6ºC and in the wheat season were 13.5 and 24.5ºC, respectively. Average annual rainfall in the area was 282 and 143 mm during the rice and wheat seasons, respectively.

2.3. EXPERIMENTAL DESIGN / TREATMENTS

The experiment consisted of five experimental treatments (crop establishment methods) with four replications arranged in a randomized complete block design. Plot size was 11 m long and 9 m wide. The treatments details for rice and wheat are shown in Table 1. Raised beds (dimensions 37 cm bed width, 15 cm bed height and 30 cm furrow width) were made in the respective treatments.

TABLE 1. DESCRIPTION OF TREATMENTS FOR RICE AND WHEAT

Treatment	Rice
PTFS/CT	Conventional transplanting on puddled flatbed (20×20 cm spacing, continuously flooded)
PTFR/CT	Transplanting on puddled flatbed {paired rows 20 cm apart (20 × 30 × 20cm)}
UPTB/D	Transplanting on unpuddled raised beds {paired rows 20 cm apart (20 × 30 × 20 cm)}
UPDB/D	Direct seeding on unpuddled raised beds {paired rows 20 cm apart (20 × 30 × 20 cm)}
UPDF/D	Direct seeding on unpuddled flatbed as zero tillage {paired rows 20 cm apart (20 × 30 × 20 cm)}

Treatment	Wheat
PTFS/CT	Conventional flatbed sowing {well pulverized soil, rows 20 cm apart (20 × 20 cm)}
PTFR/CT	Flatbed sowing {well pulverized soil, paired rows 20 cm apart (20 × 30 × 20cm)}
UPTB/D	Raised bed sowing {followed by transplanted rice, paired rows 20 cm apart (20 × 30 × 20 cm)}
UPDB/D	Raised bed sowing {followed by direct seeded rice, paired rows 20 cm apart (20 × 30 × 20 cm)}
UPDF/D	Flatbed sowing {followed by zero tilled rice, paired rows 20 cm apart (20 × 30 × 20cm)}

One micro plot was established in each replication for the ^{15}N isotopic technique. Labelled urea with 5 atom % ^{15}N provided by IAEA was applied to micro plots in solution form in three equal splits to achieve uniform field distribution. The micro plot size in flat beds was 0.8 × 1.0 m = 0.8 m^2 and in raised beds 0.67 × 1.2 m = 0.804 m^2. Enclosed micro plots were used in order to prevent lateral movement of the isotope, especially in flooded rice culture. The metal boxes were embedded into the soil to a depth of at least 25 to 30 cm and remained about 10 cm above the soil surface.

2.3. EXPERIMENTAL FIELD AND CROP MANAGEMENT

Super Basmati was the test rice cultivar and the wheat cultivar was Inqualab. Wheat was sown in November and rice was transplanted in July. About 25-day-old rice seedlings were transplanted in the respective treatments. Direct seeding was done about 20 days ahead of nursery transplanting so that total crop growth duration remained about the same.

Wheat and rice received a uniform dose of 120 kg N ha^{-1} as urea, 30 kg P ha^{-1} as triple super phosphate, 50 kg k ha^{-1} as potassium sulphate and 5 kg Zn ha^{-1} as zinc sulphate. N was applied in three equal splits. The first split of N and the full dose of P, K and Zn were applied at the time of crop sowing. The second split of N was applied at the mid tillering stage and the third split at panicle initiation. Weed control was difficult due to their rapid growth particularly during the rainy season. As chemical weeding did not provide satisfactory control, manual weeding was performed throughout the growing season to minimize yield losses.

Plants were harvested manually at ground level at maturity. Paddy was separated from straw by hand threshing to record the grain and straw weight. Representative grain and straw samples were collected after mixing and quartering. Soil samples were also collected from three depths (0–15, 15–30 and 30–45 cm) from each replication of different treatments after harvesting the rice and wheat crops. Total N, extractable NO_3^--N and NH_4^+-N were determined. Soil samples were also collected from the same three depths from each micro plot for ^{15}N analysis. The plant and soil samples were processed and ground to a fine powder. The ground samples were stored in bottles and sent to the IAEA Seibersdorf Laboratory, Austria, for ^{15}N isotope ratio analysis.

2.4. EVALUATION PARAMETERS

Irrigation water received per treatment, water saving and average water productivity were estimated. Water productivity was expressed in terms of grain production per unit of irrigation water used (kg grain ha^{-1} mm^{-1}) and was calculated by dividing the yield of each crop with the amount of water applied under each treatment.

The following parameters were utilised to assess N use efficiency: Total (grain plus straw) N uptake by crop (rice and wheat). From the isotopic data, per cent N derived from the fertilizer (%Ndff), % ^{15}N fertilizer recovery in the crops (rice and wheat) and soil (0–45 cm depth), and estimated ^{15}N fertilizer losses (unaccounted for N) from the crop–soil system were determined.

2.5. STATISTICAL ANALYSIS

All data were subjected to analysis of variance (ANOVA) and the statistical comparison of means was made using the Lsd test (P<0.05).

3. RESULTS AND DISCUSSION

3.1. PRODUCTIVITY

3.1.1. Wheat

Season and average (3 crop seasons) wheat grain and straw yields with different crop establishment methods are shown in Table 2. Grain yield ranged from 3.45 to 3.89 t ha^{-1}. There was a significant effect between years and for the interaction of treatments × years (Table 2). Mean maximum grain yield (3.89 t ha^{-1}) was produced in the PTFS/CT treatment, followed by UPTB/D (3.82 t ha^{-1}), UPDB/D (3.79 t ha^{-1}), PTFR/CT (3.62 t ha^{-1}) and UPDF/D (3.45 t ha^{-1}). Wheat sown on the well pulverized flatbed (PTFS/CT), in rows 20 cm apart, produced a significantly higher grain yield than all other treatments except UPTB/D where wheat was sown on raised beds. Wheat sown on raised beds had fewer number of rows ha^{-1} than wheat sown on the well pulverized flat bed at 20 × 20 cm spacing. The yield increase on beds is attributed to better light interception and more aeration, which are considered major factors for a good crop stand and development. The wheat straw yield obtained with zero tilled soil was significantly lowest than all other treatments. Mean maximum straw yields were obtained with treatments where wheat was sown on raised beds.

TABLE 2. EFFECT OF CROP ESTABLISHMENT METHODS ON YIELD OF WHEAT (t ha^{-1}) GROWN IN THREE SEASONS

Treatments	2002–03		2004–05		2005–06		Average	
(T)	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
PTFS/CT	3.85 a	4.24 a	3.96 a	4.12 c	3.87 a	4.77 ab	3.89 a	4.37 b
PTFR/CT	3.61 b	4.05 ab	3.57 c	4.00 d	3.67 b	4.60 bc	3.62 c	4.20 c
UPTB/D	3.89 a	4.31 a	3.82 b	4.22 b	3.77 ab	4.97 a	3.82 b	4.50 a
UPDB/D	3.94 a	4.28 a	3.76 b	4.47 a	3.68 ab	4.75 ab	3.79 b	4.50 a
UPDF/D	3.57 b	3.94 b	3.85 c	3.75 e	3.29 c	4.50 c	3.45 d	4.06 d
Lsd (P<0.05)	0.19	0.28	0.10	0.10	0.18	0.26		

F-test: Grain, year and T x year (P<0.05); Straw, year (P<0.01) and T x year (ns)

Data within a column followed by a common letter are not significantly different (P<0.05)

Wheat grain yield ranged from 3.57–3.85 t ha^{-1} in 2002–03, 3.48–3.96 t ha^{-1} in 2004–05 and 3.29–3.87 t ha^{-1} in 2005–06 (Table 2). Wheat grain yields obtained with PTFS/CT and PTFR/CT remained almost constant in all years. There was significant variation in wheat grain yield between years with UPTB/D, UPDB/D and UPDF/D; this variation showed a decrease in wheat grain yield grown in 2004–05 and 2005–06 as compared to 2002–03.

Overall reduction of wheat grain yield after three wheat crops ranged from 2–13% as compared to PTFS/CT. The average reduction of wheat grain yield was minimum (2%) in the case of raised beds while this reduction was 13% with UPDF/D (Table 2). The difference in wheat grain yield over the years was nonsignificant between PTFS/CT and UPTB/D.

3.1.2. Rice

Average (3 crop seasons) rice grain and straw yields with different crop establishment methods are shown in Table 3. Rice grain yield ranged from 3.57–4.15 t ha^{-1}. There were highly significant effects between years and for the interaction of treatments × years (Table 3). Average rice paddy yield (4.15 t ha^{-1}) with the PTFS/CT treatment was significantly higher than all other treatments (Table 3). Rice paddy yield (3.93 t ha^{-1}) of nursery transplanted on raised beds was not significantly different than the yield (3.91 t ha^{-1}) with direct seeding of rice on raised beds (Table 3). The lowest paddy yield was obtained in UPDF/D as compared to all other treatments.

All crop establishment methods produced higher paddy yield in 2003 as compared to rice crops grown in 2004 and 2005 (Table 3). The overall reduction in paddy yield after three rice crops ranged from 5.6–16.2% as compared to PTFS/CT. The reduction was 5.6% with UPTB/D, 6.3% with UPDB/D and 16% with UPDF/D (Table 3).

TABLE 3. EFFECT OF CROP ESTABLISHMENT METHODS ON YIELD OF RICE (t ha^{-1}) GROWN IN THREE SEASONS

Treatments	2003		2004		2005		Average	
(T)	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
PTFS/CT	4.28 a	5.52 a	4.06 a	4.79 b	4.13 a	4.78 a	4.15 a	5.03 a
PTFR/CT	4.03 b	4.96 b	3.81 b	4.78 b	3.70 b	4.70 a	3.85 c	4.82 b
UPTB/D	4.37 a	5.44 a	3.74 b	4.85 b	3.69 b	4.82 a	3.93 b	5.03 a
UPDB/D	4.19 ab	5.36 ab	3.81 b	5.11 a	3.72 b	4.34 b	3.91 bc	4.94 ab
UPDF/D	3.80 c	5.23 ab	3.56 c	4.75 b	3.36 c	3.88 c	3.57 d	4.62 c
Lsd (*P*<0.05)	0.19	0.46	0.11	0.14	0.17	0.17		
F-test; year and T x year (*P*<0.01)								

Data within a column followed by a common letter are not significantly different (*P*<0.05)

Rice straw yield was also affected by different crop establishment methods. Similar rice straw yields were obtained with PTFS/CT, UPTB/D and UPBD/D; the differences between these treatments were nonsignificant. The lowest rice straw yield was recorded with UPDF/D. Growing rice under aerobic soil conditions is a big challenge to avoid excessive exploitation of water in the R–W system. For this purpose, there is a need to develop new tillage and crop establishment techniques, which must be more economical and sustainable. Direct seeding / transplanting of rice on beds are new technologies which provided yield similar to conventional rice transplanting in the first rice crop (2003). Overall yield decrease by the years with UPTB/D was 5.6%, and 6.3% with UPDB/D, as compared to PTFS/CT. No lodging was observed in wheat and rice crops in the case of bed planting as a result of more light penetration in the canopy and the dry soil around the base of the plant that gave strength to the straw. The yield decrease in the second and third crops of wheat and rice could have been due to increased weed growth and more compaction of soil over time. Puddling is done for a range of reasons including weed control [15], ease of field levelling and transplanting, and to reduce percolation losses [6]. Therefore, more research on permanent bed sowing is needed to maintain the yield level similar to that of conventional rice transplanting on the major soil series of the R–W area in Pakistan. Also related issues are the life of beds and how to reshape and maintain the permanent beds in soils of different textural classes.

3.2. NITROGEN UPTAKE

3.2.1. Wheat

Accumulation of N in wheat grain was higher than accumulation in wheat straw. Nitrogen uptake in wheat grain over the years ranged from 70–85 kg ha^{-1} and in wheat straw from 29–32 kg ha^{-1} (data not shown). Mean total N uptake by wheat over three seasons ranged from 100–117 kg ha^{-1} (Table 4).

Average total N uptake was significantly higher in the PTFS/CT treatment than all other treatments, and the lowest total N uptake was observed with zero tilled soil (Table 4).

Low N uptake with UPDF/D was due to lower grain and straw yields. However, the differences of total N uptake among PTFR/CT, UPTB/D and UPDB/D were not significant.

Total N uptake by wheat was higher in the 2002–03 seasons than in the following two seasons (Table 4). Total N uptake by wheat was higher with PTFS/CT in all three wheat crops than all other treatments and it remained the lowest with UPDF/D (Table 4).

TABLE 4. EFFECT OF CROP ESTABLISHMENT METHODS ON N UPTAKE BY WHEAT (kg ha^{-1}) GROWN IN THREE SEASONS

Treatments (T)	2002–03	2004–05	2005–06	Average
PTFS/CT	119.3 a	117.7 a	112.01 a	116.6 a
PTFR/CT	114.0 ab	99.5 c	100.0 ab	104.5 bc
UPTB/D	120.1 a	107.9 abc	90.2 bc	106.1 b
UPDB/D	121.7 a	112.9 ab	87.9 bc	107.6 b
UPDF/D	111.8 b	105.6 bc	82.4 c	100.0 c
Lsd (*P*<0.05)	7.8	10.4	12.1	
F-test: Year, T x year (*P*<0.01)				

Data within a column followed by a common letter are not significantly different (*P*<0.05)

3.2.2. Rice

Nitrogen uptake in paddy over the years ranged from 46–58 kg ha^{-1} and in rice straw from 43–48 kg ha^{-1}. Accumulation of total N was higher in paddy as compared to rice straw (data not shown). Mean N uptake in paddy and rice straw was the highest in PTFS/CT and it was the lowest in UPDF/D, the latter being significantly lower than all other treatments. Total N uptake by rice over the years in different treatments ranged from 89–106 kg ha^{-1} (Table 5).

TABLE 5. EFFECT OF CROP ESTABLISHMENT METHODS ON N UPTAKE BY RICE (kg ha^{-1}) GROWN IN THREE SEASONS

Treatments	2003	2004	2005	Average
PTFS/CT	123.4 a	97.7 a	96.4 a	105.8 a
PTFR/CT	116.7 b	87.5 bc	83.6 b	95.9 b
UPTB/D	120.0 ab	89.8 abc	81.5 b	97.1 b
UPDB/D	118.6 ab	93.8 ab	79.8 bc	97.4 b
UPDF/D	109.6 c	85.0 c	73.0 c	89.2 c
Lsd (*P*<0.05)	6.0	8.4	7.4	
F-test: Year (*P*<0.01); T x year (ns)				

Data within a column followed by a common letter are not significantly different (P<0.05)

Treatment means of total N uptake were higher in wheat than rice in all treatments. Variation in N uptake by rice and wheat could be due to the differences in the growing conditions. Nitrogen uptake by rice varied with crop establishment methods. Total plant N uptake by rice grown in 2003 ranged from 110 to 123 kg ha^{-1}, 85 to 98 kg ha^{-1} in 2004 and 73 to 96 kg ha^{-1} in 2005 (Table 5). Total N uptake by rice was the highest in 2003 and the lowest in 2005. The reduction in total N uptake with the second and third season rice crops could be related to the lower paddy and straw yields obtained with time.

3.3. FERTILIZER ^{15}N RECOVERY

3.3.1. Wheat

The % N in wheat derived from the labelled fertilizer (mean data of three seasons) ranged from 29–34% (data not shown). The differences in %Ndff were not significant in all the treatments except where wheat was grown in zero tilled soil; %Ndff was significantly lower with this treatment than all other treatments. Mean treatment values of N derived from soil (Ndfs) by wheat ranged from 66–71% over the years (data not shown).

Recovery of ^{15}N labelled urea by wheat grown in 2002–03 ranged from 29–36%, from 32–40% in 2004–05 and 22–38% in 2005–06 (Table 6). The ^{15}N fertilizer recovery in the soil after wheat harvest in 2002–03 ranged from 19–32%, from 29–34% in soil after the 200405 wheat harvest and from 26–32% in soil after the 2005–06 wheat harvest (Table 6).

TABLE 6. EFFECT OF CROP ESTABLISHMENT METHODS ON ^{15}N FERTILIZER RECOVERY (%) IN WHEAT AND SOIL AT THE END OF EACH OF THREE SEASONS

Treatments (T)	2002–03		2004–05		2005–06		Average	
	Wheat	Soil	Wheat	Soil	Wheat	Soil	Wheat	Soil
PTFS/CT	36.0 a	26.2 b	37.3 ab	28.8 b	38.0 a	28.2 a	37.1 a	27.7 a
PTFR/CT	31.3 b	22.7 c	35.6 ab	33.2 a	34.6 a	31.9 a	33.8 b	29.3 a
UPTB/D	35.5 a	32.2 a	36.3 ab	31.0 ab	28.3 b	27.4 a	33.4 b	30.2 a
UPDB/D	36.2 a	32.4 a	40.4 a	30.8 ab	29.4 b	28.3 a	35.3 ab	30.6 a
UPDF/D	29.2 b	19.5 b	32.4 b	34.0 a	22.2 c	26.5 a	28.0 c	26.7 a
Lsd (P<0.05)	2.4	1.9	4.9	4.2	4.2	18.3		

F-test: Wheat, year and T x year (P<0.05); Soil, year and T x year (ns)

Data within a column followed by a common letter are not significantly different (P<0.05)

Mean (data from three seasons) recovery of ^{15}N labelled urea by the wheat crop varied from 28%–37%. Mean fertilizer N utilization from ^{15}N urea by wheat was similar in PTFS/CT and UPTB/D and was lowest in the zero tilled soil, which was significantly lower than in all the other treatments. Recovery of ^{15}N fertilizer by wheat was low compared to the values reported by other researchers. It was reported that ^{15}N fertilizer use efficiency by wheat was 21% when 200 kg N ha^{-1} was applied [16]. The majority of the literature suggests that the difference method gives higher values of N recovery efficiency than the isotopic dilution method [17, 18, 19], but this discrepancy appears to be more common in flooded rice [20]. Low estimates of ^{15}N recovery were likely due to rapid pool substitution [21]. The difference method provides an estimate of N recovered from both fertilizer and other N sources [22]. Thus with the difference method it was not possible to partition the plant N between fertilizer or soil sources.

The total ^{15}N recovery from the soil in wheat ranged from 27–31% over the years. The major proportion of ^{15}N fertilizer recovered from the soil was found in the top layer (0–15 cm) with much less in the lower layers (data not shown). Mean data from ^{15}N fertilizer recovery in wheat and soil and estimated losses (unaccounted for N) for the experimental treatments are displayed in Fig.1. Total losses of ^{15}N fertilizer in the wheat–soil system ranged from 34–45%. The highest losses of ^{15}N fertilizer were observed with UPDF/D and the lowest losses with UPDB/D. The ^{15}N fertilizer losses were not significantly different between UPDB/D, PTFS/CT, PTFR/CT and UPTB/D.

3.3.2. Rice

Mean %Ndff ranged from 18–25% over the years in rice (data not shown). There was a significant increase in %Ndff in PTFS/CT and PTFR/CT as compared to treatments where rice was grown as UPTB/D, UPDB/D and UPDF/D; however, the difference in %Ndff between UPTB/D and UPDB/D was not significant. Per cent Ndff in rice straw was the lowest with UPDF/D.

Mean values of N derived from soil (%Ndfs) by rice ranged from 75–82% over the years (data not shown). This indicated that rice straw took more N from the soil. Plant N values derived from the fertilizer were the lowest where rice was grown as UPDF/D meaning that fertilizer availability in this treatment was less. This may be due to soil compaction as the paddy and straw yields were low with this treatment.

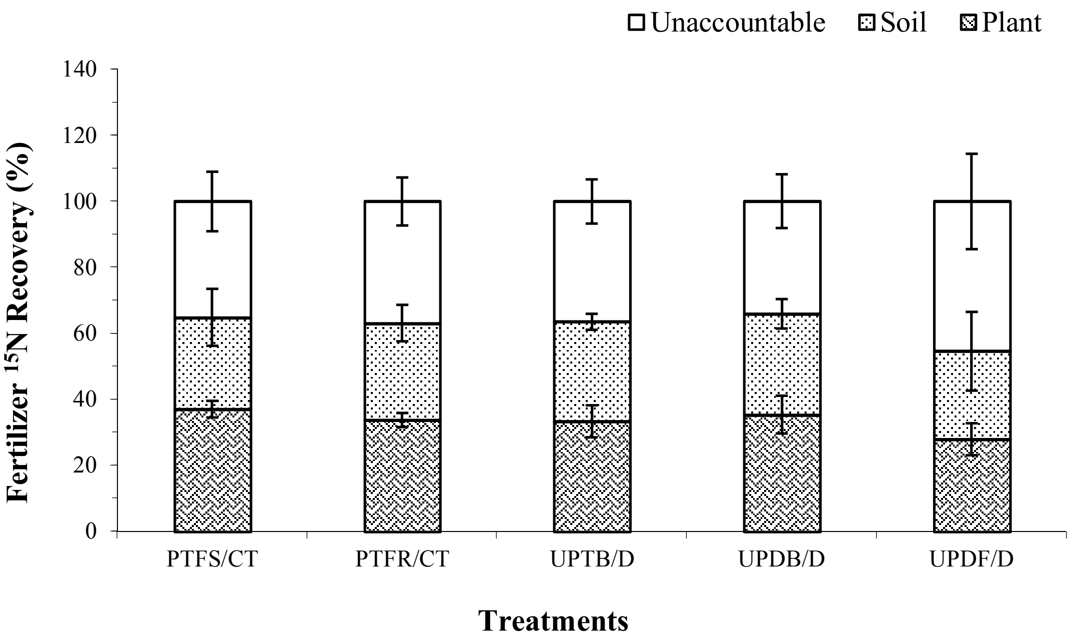

FIG. 1. Fate of fertilizer ^{15}N applied to wheat crops (mean of three years). Lsd bars P<0.05.

Recovery of ^{15}N labelled urea by the rice crop grown in 2003 ranged from 21–29%, from 18–28% in 2004 and from 12–26% in 2005 (Table 7). The ^{15}N fertilizer recovered in the soil after rice harvest in 2003 ranged from 21–30%, from 29–39% after rice harvest in 2004 and from 30–36% after rice harvest in 2005 (Table 7).

TABLE 7. EFFECT OF CROP ESTABLISHMENT METHODS ON ^{15}N FERTILIZER RECOVERY (%) IN RICE AND SOIL AT THE END OF EACH OF THREE SEASONS

Treatments	2003		2004		2005		Average	
	Rice	Soil	Rice	Soil	Rice	Soil	Rice	Soil
PTFS/CT	29.1 a	21.3 b	28.2a	28.6c	25.7a	31.1a	27.6 a	27.0 d
PTFR/CT	24.6 c	22.3 b	27.1a	31.7b	21.9b	30.4a	24.5 b	28.2 cd
UPTB/D	27.9 ab	30.0 a	23.5a	29.9bc	17.2c	30.1a	22.9 c	30.0 bc
UPDB/D	26.5 b	28.0 a	23.7a	37.4a	16.5c	36.1a	22.2 c	33.8 a
UPDF/D	21.4 d	21.1 b	17.7b	38.6a	11.6d	36.3a	16.9 d	32.0 ab
Lsd (*P*<0.05)	1.8	2.9	4.6	2.9	1.6	6.7		
F-test: Rice and wheat, year and T x year (*P*<0.05)								

Data within a column followed by a common letter are not significantly different (*P*<0.05)

Mean data of recovery of ^{15}N fertilizer by rice ranged from 17 to 28% (Table 7). The recovery of ^{15}N by paddy was higher than straw in all the treatments. Recovery of ^{15}N fertilizer by rice was highest (28%) in PTFS/CT, followed by PTFR/CT (25%). The ^{15}N recovered by rice was similar in both raised bed treatments; being 23% in UPTB/D and 22% in UPDB/D. Total ^{15}N recovered by rice in the case of UPDF/D was 17% which was significantly lower than all other treatments.

The % ^{15}N fertilizer recovery in soil after rice harvest ranged from 27–34% over the years. Recovery of ^{15}N fertilizer in the soil with raised bed establishment was higher as compared to other treatments. A major fraction (62%) of the ^{15}N fertilizer recovered from the soil was found in the top layer (0–15 cm) and less at 30–60 cm. The overall ^{15}N fertilizer recovery in the soil after rice harvest was higher than that of plant recovery. The variation in ^{15}N fertilizer recovery suggested the differential effects of the crop establishment methods.

Total estimated losses (unaccounted for) of ^{15}N fertilizer from the rice–soil system ranged from 44–51% (Fig. 2). The highest losses were observed with UPDF/D and the lowest with UPDB/D.

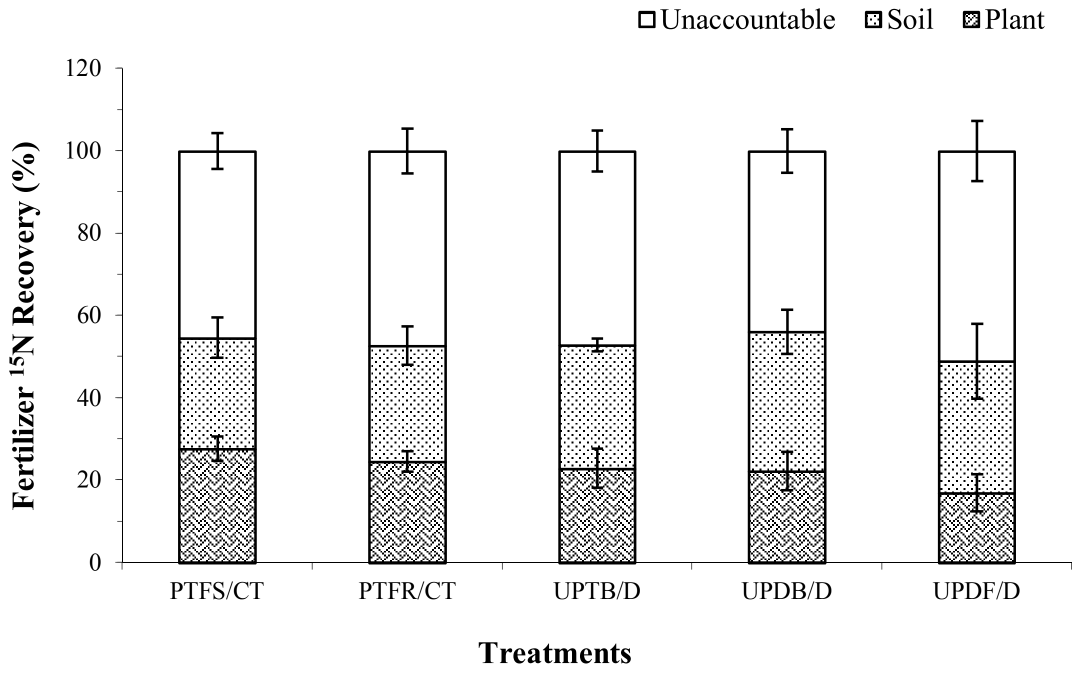

FIG. 2. Fate of fertilizer ^{15}N applied to rice crops (mean of three years). Lsd bars P<0.05.

3.4. WATER PRODUCTIVITY

3.4.1. Wheat

All the treatments were irrigated at the same time, and thus the number of irrigations was the same for all crop establishment methods. The total amount of water received by all the treatments ranged from 322–359 mm (Table 8). More water savings were achieved with raised beds compared to the conventional wheat sowing method, the savings ranging from 1.3 to 18%.

Mean irrigation water productivity for wheat ranged from 10.5–12.9 kg grain ha^{-1} mm^{-1} water (Table 8). Water productivity was higher (12.9 kg grain ha^{-1}mm^{-1}) in raised beds as compared to conventional flatbed sowing of wheat (11.1 kg grain ha^{-1}mm^{-1}).

TABLE 8. INFLUENCE OF CROP ESTABLISHMENT METHOD ON THE WATER PRODUCTIVITY OF WHEAT

Treatment	Irrigation water (mm)	Rainfall (mm)	Total water (mm)	Grain yield (kg ha^{-1})	Water productivity (kg grain ha^{-1} mm^{-1})
PTFS/CT	214	145	359	3894	11.2
PTFR/CT	210	145	355	3615	10.5
UPTB/D	164	145	309	3823	12.9
UPDB/D	163	145	308	3791	12.9
UPDF/D	177	145	322	3445	11.2

3.4.2. Rice

Water shortage is a major issue for sustaining and increasing the productivity of R–W systems. Combined water productivity of irrigation plus rainfall for rice is given in Table 9. Rice grown on flat beds (PTFR/CT and UPDF/D) and raised beds (UPTB/D and UPDB/D) were irrigated at the same time, while the PTFS/CT treatment received irrigation water at different intervals to keep the field under flooded condition; thus, the amount of water applied in this treatment was higher than all other crop establishments. The mean amount of water for transplanted rice on beds was 1704 mm and for direct seeded rice on beds was 1726 mm. The total amount of water received was higher with UPDB/D than UPTB/D as the crop duration was longer in direct seeded rice. The amount of water applied to raised beds was less than the amount of water applied to flatbed crop establishments. Water saving in all treatments ranged from 15 to 33% over PTFS/CT (Table 9). The saving was more in raised beds as compared to flat beds. The maximum water saving (30%) was with UPTB/D and the minimum (15%) with PTFR/CT.

TABLE 9. INFLUENCE OF CROP ESTABLISHMENT METHOD ON THE WATER PRODUCTIVITY RICE

Treatment	Irrigation water (mm)	Rainfall (mm)	Total water (mm)	Grain yield (kg ha^{-1})	Water productivity (kg grain ha^{-1} mm^{-1})
PTFS/CT	1953	307	2260	4145	1.8
PTFR/CT	1654	307	1961	3851	2.0
UPTB/D	1397	307	1704	3912	2.3
UPDB/D	1419	307	1726	3926	2.3
UPDF/D	1545	307	1852	3573	1.9

Water productivity for rice ranged from 1.84–2.30 kg grain ha^{-1} mm^{-1} water. Water productivity with PTFR/CT was 6.5% higher than PTFS/CT. Transplanted and direct seeded rice on permanent raised beds gave almost similar water productivity values. The water productivity increase over PTFS/CT for UPTB/D was 25% and 23.4% for UPDB/D. Water productivity values, obtained with raised beds either direct seeded or transplanted rice, suggests that adoption of bed planting of rice is an attractive option to save water without any yield loss as compared to PTFS/CT. However, in this study the mean loss in paddy yield with raised beds was about 6%, which could be eliminated by refining the bed technology i.e., reshaping of beds, duration of permanent beds with respect to soil type.

4. CONCLUSIONS

The performance of several crop establishment techniques were compared with the conventional method of rice and wheat cultivated during three consecutive R–W cycles at Lahore, Rice Research Station, Kala Shah Kaku in Pakistan.

Crop establishment techniques had differential effects on rice and wheat grain yields. On average, reduction of wheat grain was only 2% with UPTB/D and 3% with UPDB/D as compared to PTFS/CT, whereas the saving of water with raised beds (UPTB/D and UPDB/D) was about 18% over PTFS/CT. Although, paddy yield on raised beds was 6% lower than the yield obtained with PTFS/CT, water savings with raised beds was about 32% over the conventional method of rice transplanting.

Mean irrigation water productivity for wheat ranged from 10.5–12.9 kg grain ha^{-1} mm^{-1} water. Water productivity was higher (12.9 kg grain mm^{-1}) in raised beds as compared to conventional flatbed sowing of wheat (11.1 kg grain ha^{-1} mm^{-1}). Water productivity for rice ranged from 1.84–2.30 kg grain ha^{-1} mm^{-1} water. The highest rice water productivity values (2.3 kg grain ha^{-1} mm^{-1} water) were obtained with raised bed either direct seeded or transplanted rice. In both crops, estimated water productivity was higher in raised beds than in flat beds. Therefore, raised bed planting resulted in water and energy savings at the farm level with some yield penalty.

Data on N derived from the ^{15}N-labelled urea fertilizer (%Ndff) in wheat (29–34%) were higher than those in rice (18–25%). Significantly lower %Ndff was measured in wheat with zero tilled soil than all other treatments. A similar trend was found in the rice crop.

Fertilizer ^{15}N recovery by rice ranged from 17–28%, and in wheat from 28–38%. In both crops the highest fertilizer ^{15}N recovery was achieved with the conventional method of sowing / transplanting while the lowest was obtained when the crop was grown on a flatbed in zero tilled soil. The amount of ^{15}N fertilizer recovered in the soil was high in the 0–15 cm layer and declined with depth up to 45 cm. The percentage of ^{15}N recovered from soil (0–45 cm) after rice harvest ranged from 21–34% and from 26–32% after wheat harvest. The estimated mean ^{15}N fertilizer losses (unaccounted for N) were higher in rice (46.4%) than in wheat (36.7%).

Overall, these data suggested that wheat and rice can be grown on permanent beds without significant yield loss. Further research to refine the bed technology, in particular its adaptation to different soil types is needed.

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INFLUENCE OF WATER REGIME, MULCHING AND FERTILIZER NITROGEN MANAGEMENT ON NITROGEN AND WATER USE EFFICIENCY FOR SUSTAINABLE RICE–WHEAT ROTATION SYSTEMS IN SOUTH-WESTERN CHINA

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Abstract

About 9.5 million hectares (ha) are cultivated to rice–wheat in several regions of China. The rice–wheat (RW) rotation is the predominant agricultural system in South-western China. However, the productivity and sustainability of the system is threatened by soil degradation and water shortage. Two field experiments were conducted on a purple earth soil in Wenjiang county, South-western China to investigate the effect of water regime and straw and fertilizer N management on nitrogen and water use efficiencies of the rice–wheat cropping system. Treatments included conventional flooded, no mulch treatment (FNL), non-flooded, no mulch treatment (ANL), non-flooded, plastic mulching treatment (AML) and non-flooded, straw mulching treatment (ASL). ^{15}N enriched fertilizers (180 kg N ha^{-1} for rice and 120 kg N ha^{-1} for wheat) were applied in micro plots to measure the fertilizer N recovery by the rice and wheat crops and the balance of the applied fertilizer N in the crop–soil system. In experiment 1 ^{15}N labelled urea (5 atom % ^{15}N) was the N source whereas in experiment 2 two N sources, i.e. ^{15}N labelled ammonium sulphate (9.8 atom % ^{15}N) and ^{15}N labelled potassium nitrate (10.0 atom % ^{15}N) were applied. In experiment 1, soil water content monitored with a neutron probe during the rice season was high in the top 0–10 cm layer, and declined with depth. Generally, the water content in each soil layer was higher with FNL than ANL or ASL, indicating that the imposed water regime was very important for the maintenance of soil water content. For the mulched treatments AML and ASL, soil water content was higher in the top 10 cm of soil, compared with ANL, indicating that plastic and straw mulching have the potential to prevent evaporation losses from the soil. Non-flooded plastic mulching had a similar effect on rice yield, N uptake, fertilizer N recovery and water use efficiency as conventional flooded, no mulch rice. The yield of rice decreased by 10–15% in the non-flooded, no mulch cultivation treatment, but straw mulching did not significantly decrease rice yield in the 3rd and 4th years. Wheat yields were not affected by mulching. Urea-N recovery by flooded rice was on the average 22–25% of applied N and estimated N losses were 39–45% of the applied N. Non-flooded cultivation did not significantly affect the urea-N recovery by rice, but significantly decreased the residual fertilizer N in the soil, resulting in an increased N loss from the soil–plant system. Non-flooded rice cultivation with straw mulching

decreased urea-N recovery by rice but increased the soil residual fertilizer N, thus resulting in decreased N loss from the soil–plant system. Urea-N recovery by wheat was on the average 37–44% of the applied N and estimated N losses were 18–29% of the applied N. Non-flooded pre-treatment did influence the wheat fertilizer N recovery; less fertilizer N was recovered while soil N recovery was similar thus resulting in higher N losses from the system compared to the flooded treatment. Water use efficiency for rice was much lower than that of winter wheat. The wheat water use efficiency was related to the water regime from the previous cropping season.

In experiment 2, regardless of the flooding conditions, rice/wheat crops could recover significantly more NH_4^+-N than NO_3^--N, and the soil immobilized more NH_4^+-N than NO_3^--N, so the loss with NH_4^+-N was significantly less than that of NO_3^--N. In the non-flooded straw mulching treatment, rice/wheat recovered significantly less N from NH_4^+-N or NO_3^--N while the soil residual N was significantly more than that of the flooded only treatment, especially for NH_4^+-N. Conventional flooded rice took up more N from NH_4^+-N or NO_3^--N than non-flooded rice, while recovery of NH_4^+-N or NO_3^--N and soil residual N in the wheat season were not different between flooded and non-flooded treatments.

1. INTRODUCTION

The cultivated areas of rice–wheat cropping in China are estimated at about 9.5 million hectares, which contribute some 430 000 tonnes of annual grain production. These areas are mainly located in the East, North and South-western parts of the country. No till wheat is grown in some of these areas. In Southwest (SW) China, the rice–wheat rotation is the predominant agricultural system. The yield of the rice–wheat rotation system was initially very high, but it seems to be declining over the past few years, due to soil degradation, including a decrease in soil organic matter, nutrient deficiencies, salinization and seasonal water shortages (lower ground water table and less availability of surface water). Other yield constraints are the low N recovery by the rice crop (about 25% of the applied fertilizer N) and the consequent high losses from the soil–plant system (35–50% of applied fertilizer N) due to improper application methods of fertilizer N, such as topdressing rates of over 300 kg N ha^{-1}. Furthermore, wheat straw is always burnt because of the very short time interval between wheat harvest and rice transplanting leading to serious atmospheric pollution. These problems need to be addressed through proper management of irrigation water, N fertilizer and crop straw with the overall aim at optimizing yield and minimizing external inputs in the intensive rice–wheat rotation system.

Field trials on dry cultivated rice and plastic film mulched treatments were conducted in the mid-1980s [1] and non-flooded cultivation of rice was proposed as one approach to overcome the water shortage problems [2]. Some studies on the fate of fertilizer N in wetland rice using ^{15}N techniques have been conducted [3]. Soil fertility may be influenced by mulching in dryland cropping [4]. Mulching has been proposed as one alternative practice for irrigated rice under dryland cultivation due to water savings [5]. A review of the work on mulching in rice cultivation was made in 2000 [6]. It was concluded that film or straw mulching practices would contribute to soil water protection, temperature maintenance, soil fertility improvement, crop growth enhancement and yield increase [7, 8, and 9].

The specific effects and interactions of cultivar, nitrogen and water on productivity, nitrogen use efficiency (NUE) and nitrogen balance have been studied for the rice–wheat sequences of Bangladesh [10]. Conflicting results on the effects of wheat straw mulching on rice yields in SW China have been reported [11]. Another study found that rice yields decreased by 16% with wheat straw mulching under non-flooded conditions compared to the traditional flooding at low N input, but they were comparable to those under traditional flooding cultivation at high N input (>150 kg N ha^{-1}) [12,13]. Studies on the interactions between N application rates and mulching in dryland farming as well as the influence of mulching on the utilization rate of N fertilizer by rice have been recently conducted [14]. The authors found that the fertilizer N recovery with normal irrigation cultivation (15.3%) was lower than that of dryland rice without plastic mulching (23.6%) or with plastic mulching (23.1%), and the latter was significantly higher than that with straw mulching (19.1%) or straw plus film mulching (18.4%).

The objective of this study was to investigate the influence of improved irrigation, N fertilization and mulching management practices to enhance sustainable production of rice–wheat rotations in SW China through better use efficiency of external inputs and reduced environmental pollution.

2. MATERIALS AND METHODS

Two field experiments were conducted on a purple earth soil in Wenjiang County, South-west China. The first experiment investigated the effect of water regime and mulching management on fertilizer nitrogen and water use efficiencies of the rice–wheat system over four consecutive seasons, during the period 2002–06. The second experiment was set up to study the influence of fertilizer N sources on rice–wheat crop yields and the fate of fertilizer N in the rice–wheat system (during the last season 2005).

2.1. EXPERIMENT1

2.1.1. Experimental site

The field experiment was located at the Agricultural Experimental Station of the Sichuan Academy of Agricultural Sciences, Wen Jiang county (30°50'N, 103°45'E) on a purple earth soil. Ten soil samples (0–50 cm) were collected from the site, bulked and analysed for physical and chemical characteristics (Table 1).

TABLE 1. SOIL CHARACTERISTICS IN THE EXPERIMENTAL FIELD

Soil depth (cm)	pH	OM ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Olsen–P ($mg\ kg^{-1}$)	Avail. K ($mg\ kg^{-1}$)	Field capacity ($g\ kg^{-1}$)	Bulk density ($g\ cm^{-3}$)
0–10	6.8	2.18	1.7	17.7	37.9	446	1.20
10–20	7.0	1.98	1.7	17.7	37.9	435	1.18
20–30	7.0	1.78	1.4	15.7	36.3	295	1.50
30–40	7.1	1.67	1.4	15.4	34.4	202	1.51
40–50	7.1	1.45	1.3	14.7	32.0	195	1.47

OM, organic matter

Prior to initiation of the field experiment on 29 April 2002, the silty loam paddy field had been cropped to a rice–wheat rotation for many years and had not been used for any fertilizer experiment. The ground water level was at 1~2 m depth in the winter wheat season and 0.5~1 m in the rice season.

2.1.2. Climatic conditions

The climate is subtropical, with 15–18°C yearly mean temperature, 950–1 200 mm average annual rainfall, 280–320 frost free days and 1 000–1 400 solar hours. The spring and summer drought is a serious constraint for wheat production.

2.1.3. Experimental design/treatments

The treatments of the field experiment 1 are described in Table 2.

TABLE 2. TREATMENTS OF WATER REGIME, NITROGEN AND MULCH MANAGEMENT FOR RICE IN THE FIELD EXPERIMENT

Treatment	Water regime	Mulching methods	Water management
FNL	Flooded	None	Flooded
ANL	Non-flooded	None	Monitoring irrigation
ASL	Non-flooded	Straw	Monitoring irrigation
AML	Non-flooded	Plastic membrane	Monitoring irrigation

[a]The same management as traditional flooded paddy rice.

[b]Transplanting into puddled soil. Irrigation water was applied to rice when the soil water content was lower than 75% of field capacity at commencement of tillering, booting stage, flowering stage and soft dough grain stage.

2.1.4. Field and crop management

The rotation system comprised winter wheat and rice (head crop) using local cultivars of rice (*Oryza sativa*), Hybrid 527 (2002, 2003), Chuangxiang No 3 (2004, 2005) and winter wheat (*Triticum aestivum*), cultivar SW3243 for all the growing seasons.

For the rice crop, a total of 180 kg N ha^{-1} as urea was applied as follows: 30 kg N ha^{-1} was applied at sowing, 100 kg N ha^{-1} was applied as a basal application at transplanting and 50 kg N ha^{-1} was applied as a top dressing at the commencement of tillering. For the wheat crop, a total of 120 kg N ha^{-1} was split into 60 kg N ha^{-1} at sowing and a further 60 kg N ha^{-1} at the commencement of tillering.

Immediately after the wheat harvest, the field was puddled with 40–45 mm of water and 16 plots of 6 × 7 m were established. These were separated by a plastic membrane buried to 60 cm depth to prevent water movement from one plot to another. Neutron access tubes and suction cups were installed in each plot at 50 and 60 cm depth, respectively. One rectangular stainless steel micro plot of 1.2 × 0.75 m with sides 40 cm high was installed in each plot for the ^{15}N isotopic technique. The top of the micro plot was 15 cm above the soil surface. After harvest of each wheat crop the field was puddled with 40–45 mm of water. The micro plots were moved to a new location in the same plot in each new cropping season. ^{15}N-labelled urea with 5.0 atom % ^{15}N was provided by the International Atomic Energy Agency.

^{15}N-labelled urea and unlabelled urea, at a rate equivalent to 100 kg N ha^{-1}, was applied just before rice transplanting, in micro plots and plots respectively. Phosphorus and potassium fertilizers were also applied at rates equivalent to 75 kg P_2O_5 ha^{-1} and 75 kg K_2O ha^{-1}, respectively. N, P and K fertilizers were applied in the form of urea, superphosphate and potassium sulphate, respectively. All fertilizers were mixed thoroughly with the top 10 cm of soil.

Before wheat seeding, ^{15}N-labelled urea and unlabelled urea (60 kg N ha^{-1}) was diluted with water and sprayed onto the soil surface in the micro plots and plots, respectively. Phosphorus and potassium fertilizers were applied as above in the planting holes at rates equivalent to 72 kg P_2O_5 ha^{-1} and 68 kg K_2O ha^{-1}, respectively.

Rice seed was sown after ^{15}N-urea was applied at 30 kg N ha^{-1}, and mixed with the soil in the micro plot. A similar procedure was used with unlabelled urea in the rest of the plot. Wheat seeds were no till sown into holes spaced 10 cm apart within rows spaced either 25 cm or 15 cm apart.

After basal fertilization either a thin plastic film or 5 000 kg ha^{-1} of straw was mulched onto the corresponding plots and micro plots. Rice seedlings were transplanted at a spacing of 20 cm in rows 30 cm apart.

The flooded rice treatment received 106, 118, 555 and 754 mm of irrigation water and 572, 643, 590 and 349 mm of rainfall in the 2002, 2003, 2004 and 2005 seasons. Wheat received 170, 190, 337 and 481 mm of rainfall in the 2002/03, 2003/04, 2004/05 and 2005/06 seasons, respectively.

An application of urea at 50 or 60 kg N ha^{-1} was applied at the commencement of tillering of rice, and wheat, respectively. The ^{15}N-urea or unlabelled urea was diluted with water and sprayed onto the soil surface for all treatments.

Monitoring of soil water status was made using a neutron probe. Approximately every 10 days during the rice season, and every month in the wheat season, the volumetric water content at 0–10, 10–20, 20–30, 30–40 and 40–50 cm was measured by a NMG-3D neutron probe, and soil water was removed from the suction cups for measurement of nitrate concentration.

Calibration of counts of slow neutrons and soil water content were undertaken at several locations in the plots. Immediately after counting, soil was sampled from 0–10, 10–20, 20–30, 30–40 and 40–50 cm and oven dried at 105^{o}C for determination of gravimetric soil water content. The following linear equation was used for calibration:

$$\theta = a + b\,(R / R_s)$$

Where: θ is the volumetric water content (cm^3 cm^{-3}), a is the intercept, b is the slope, R is the actual count rate and R_s is the standard count rate, measured in the shield.

2.1.5. Harvesting, sampling and analysis

Rice harvests were made from 1.0 m^2 areas at maximum tillering, 50% flowering, soft dough stage, and maturity. All aboveground parts of plants in the micro plots were carefully cut, oven dried at 105°C for half an hour and at 70°C until dryness. After drying, dry matter yields and yield components were measured. After separation, the plant samples were ground, and total N concentration of the grain, husk and straw was measured by the Kjeldahl method, and ^{15}N abundance was determined with a MAT 251 Mass Spectrometer. Soil in the micro plots was sampled at 0–20, 20–40 and 40–60 cm, dried at room temperature and total N and ^{15}N abundance measured.

Wheat was harvested one week after 50% flowering (Z-30), at the dough grain stage and at maturity. One m^2 of above ground plant parts were cut for measurement of dry matter and nitrogen concentration. Yield component characteristics were determined at the maturity harvest. Plant and soil samples from the micro plots were collected and processed as for rice.

2.1.6. Evaluation parameters

Water use efficiency, WUE (kg grain ha^{-1} mm^{-1} water) was calculated as:

$$WUE = G / (I + R)$$

Where G is grain yield in kg ha^{-1} and I and R are irrigation and rainfall in mm.

or WUE can be expressed as: kg grain m^{-3} water = kg grain ha^{-1} mm^{-1} water / 10

NUE (%) = 100 x (Total excess ^{15}N uptake by crop / total ^{15}N excess of fertilizer applied)

2.1.7. Statistical analysis

All the data were subjected to analysis of variance (ANOVA) using the SAS package and the statistical comparison of means was made using the Duncan Multiple Range Test (DMRT) at $P<0.05$.

2.2. EXPERIMENT 2

Experiment 2 was conducted during the 2005 rice season and subsequent 2005/06 wheat season. All treatments and field management operations were similar to those described above for Experiment 1 except for the forms of fertilizer N used to compare the fate of ammonium-N and nitrate-N under the experimental conditions.

^{15}N labelled NH_4^+-N as $(^{15}NH_4)_2SO_4$ with 9.8 atom % ^{15}N abundance and ^{15}N labelled NO_3–N as $K^{15}NO_3$ with 10.0 atom % ^{15}N abundance provided by the Shanghai Chemical Research Institute were the fertilizer N sources applied.

3. RESULTS AND DISCUSSION

3.1. EXPERIMENT 1

3.1.1. Change of water content in relation to mulch and water management

During the 2002 rice season the soil water content was very high (approximately 38%) in the top 0–10 cm layer and it declined sharply from the topsoil to lower layers (Fig. 1).

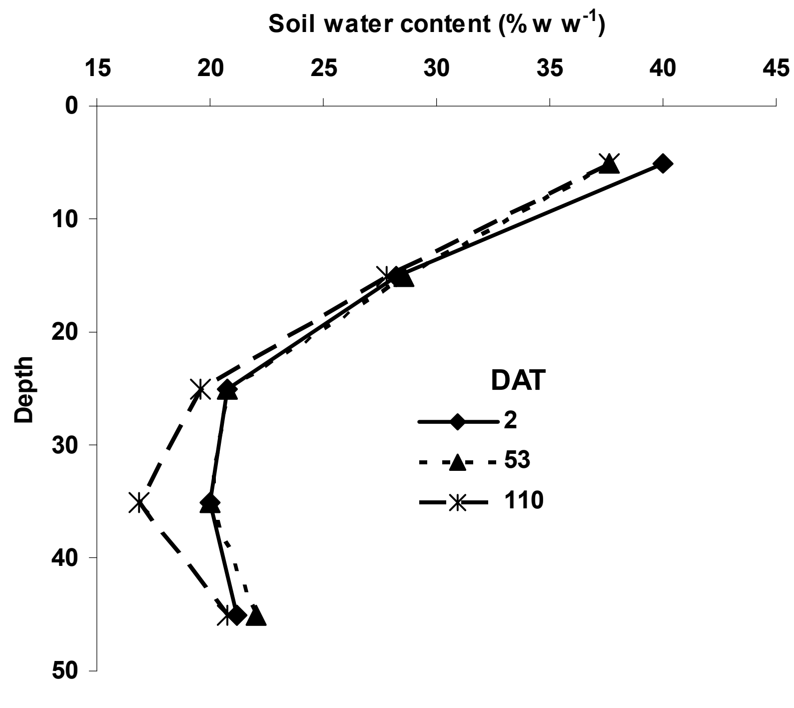

FIG. 1. Soil profile (0–50 cm) water content during the 2002 rice season.

In the FNL treatment the soil water content remained high throughout the whole vegetative period, especially in the top 10 cm of soil (Fig. 2). Compared with the flooded FNL treatment, soil water content for the ANL treatment was lower, by 1–2%. In the AML treatment, the soil water content was higher in the top 10 cm but lower in the other layers in comparison to the ANL treatment, especially in the 2002 rice season. This was probably due to the plastic or straw mulch preventing water from evaporating which maintained the high water content in the topsoil.

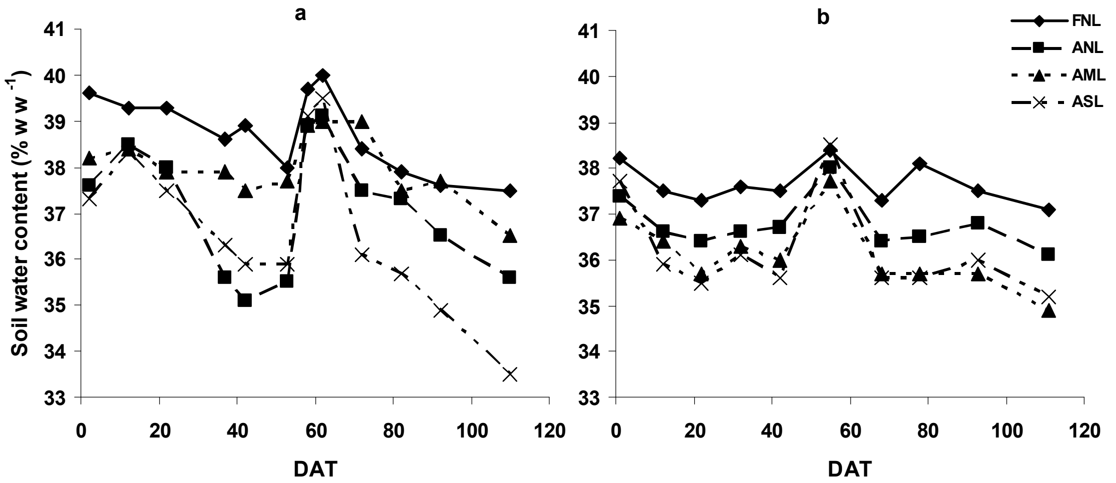

FIG. 2. Soil water content of the 0–10 cm soil layer during the rice season of 2002 (a) and 2003 (b).

In the treatments where more irrigation was applied in the previous season (FNL), the soil water content in the top 10 cm of soil was higher than in the other treatments (ANL and ASL), but it was similar in the 10–20 cm and lower soil layers (Fig. 3).

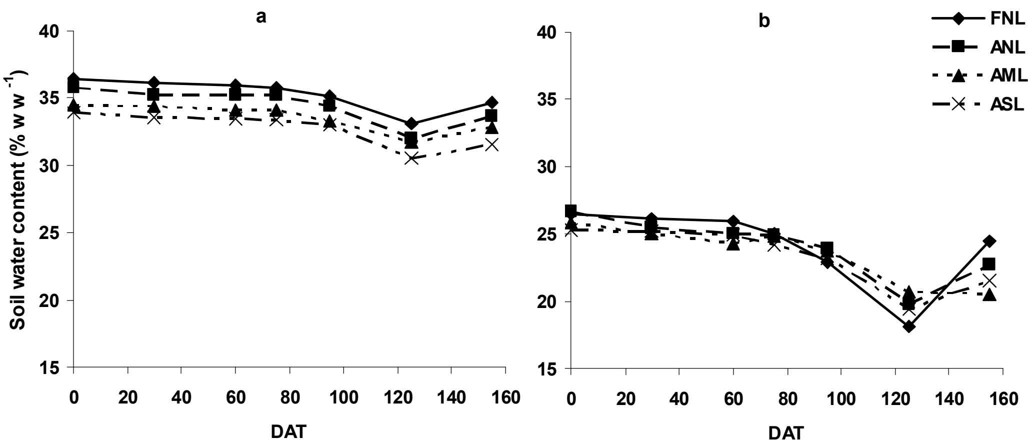

FIG. 3. Soil water content of the 0–10 cm (a) and 10–20 cm (b) soil layers for the 2003 wheat season.

3.1.2. Crop dry matter and N uptake as affected by fertilizer, mulch and water management

The above ground dry matter yield of rice in the FNL treatment, was similar to that in the AML treatment. The ASL and ANL yields were significantly lower than the FNL treatment (Table 3).

TABLE 3. ABOVEGROUND DRY MATTER YIELD (g m^{-2}) OF RICE OVER FOUR SEASONS

Treatment	2002	2003	2004	2005	Mean
FNL	1572 a	1286 a	1254 ab	1456 b	1392
ANL	1428 b	882 c	1222 b	1354 c	1222
AML	1577 a	1264 a	1314 a	1546 a	1425
ASL	1345 c	917 c	1125 c	1236 d	1156

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$.

Dry matter accumulation of rice at each sampling stage was similar between the AML and the FNL treatments (Fig. 4) and significantly higher than that of the non-flooded without straw mulching (ANL) treatment, which was significantly higher than that in the ASL treatment, especially at the early growth stage (Fig. 4), indicating that straw mulching limited the growth of rice, probably due to lower temperatures at the soil surface and at 10 cm depth.

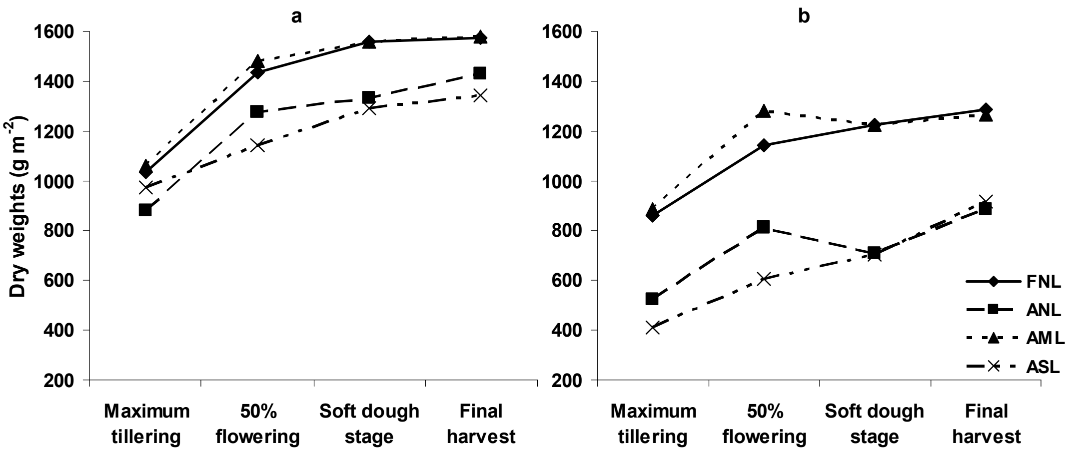

FIG. 4. Above ground dry matter accumulation of rice at different growth stages in 2002 (a) and 2003 (b) seasons.

The N uptake of rice was not significantly different between the FNL and AML treatments (Table 4). This may be due to the plastic covering increasing crop growth and nutrient uptake. When rice grew under non-flooded conditions, with or without straw mulching (ASL, ANL), N uptake was significantly lower than in the above two treatments (FNL and AML) most likely due to the lower availability of N in the soil resulting from non-flooded conditions.

TABLE 4. NITROGEN UPTAKE (kg N ha^{-1}) IN ABOVEGROUND PARTS OF RICE OVER FOUR SEASONS

Treatment	2002	2003	2004	2005	Mean
FNL	160.0 ab	134.2 a	139.2 ab	165.4 a	152.3
ANL	145.0 b	92.9 b	134.4 b	148.3 b	141.4
AML	179.0 a	133.6 a	141.6 a	169.7 a	155.7
ASL	143.0 b	110.0 ab	125.3 c	136.2 c	130.8

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$.

The mean dry matter yields of winter wheat in the previous straw mulching non-flooded rice treatment (ASL) were not significantly different from that in the previously flooded treatment (FNL), both at maturity and other vegetative stages (Table 5), suggesting that the rice straw mulching could increase the growth of subsequent wheat crops, probably due to the benefits of straw decomposition.

TABLE 5. ABOVEGROUND DRY MATTER YIELD (g m^{-2}) OF WHEAT OVER FOUR SEASONS

Treatment	2002–03	2003–04	2004–05	2005–06	Mean
FNL	863 a	1304 a	890 a	1119 b	1044
ANL	730 b	1174 b	797 b	1071 b	943
AML	729 b	1123 b	875 a	1215 a	986
ASL	792 ab	1417 a	814 b	1105 b	1032

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$.

In the 2002–03 wheat seasons, N uptake was significantly lower in the AML treatment than in FNL (Table 6). In the 2003–04 wheat season, N uptake in the straw mulching, non-flooded treatment (ASL) was similar to FNL and significantly higher than that in ANL and AML, indicating that straw mulching could promote crop N uptake one year after application. In the 2004–05 and 2005–06 seasons, N uptake in the FNL treatment was not significantly higher than that in ASL, indicating that wheat could restore its uptake ability from the non-flooding and straw mulching treatments after several cropping seasons.

TABLE 6. N UPTAKE (kg ha^{-1}) BY WHEAT OVER FOUR SEASONS

Treatment	2002–03	2003–04	2004–05	2005–06	Mean
FNL	120.5 a	158.7 a	108.1 a	131.8 ab	120.0
ANL	106.6 ab	119.5 c	92.9 b	126.6 b	109.8
AML	97.3 b	109.0 c	109.8 a	137.9 a	123.9
ASL	117.6 ab	162.7 a	103.1 a	125.6 b	114.4

Data within a column followed by the same letter are not significantly different, DMRT at P<0.05.

3.1.3. Grain yield and yield components in relation to fertilizer, mulch and water management

Rice grain yield of the ANL treatment was reduced by approximately 10–15% after the change from the FNL conventional treatment (Table 7). The yield in the non-flooded straw mulching treatment (ASL) was significantly lower than that of FNL in 2002 and 2003 due to a decrease in filled ear number (Table 8), but not significantly lower than those of FNL for 2004 and 2005 due to an increase in grain number per ear, most likely resulting from increased inputs of organic matter and nutrients with time from straw mulching.

TABLE 7. GRAIN YIELD (kg ha^{-1}) OF RICE OVER FOUR SEASONS

Treatment	2002	2003	2004	2005	Mean
FNL	8611 a	6230 b	8570 a	7451 a	7716
ANL	7384 c	5556 c	7710 b	6570 b	6805
AML	8543 a	7463 a	7120 b	7009 ab	7534
ASL	7814 b	5635 c	8010 ab	6899 ab	7090

Data within a column followed by the same letter are not significantly different, DMRT at P<0.05.

TABLE 8. TOTAL AND RATIO OF VIABLE TO TOTAL EAR NUMBER PLANT^{-1} FOR THE RICE CROP IN THE 2003 SEASON

Parameter	FNL	ANL	AML	ASL
Ear number plant^{-1}	9.4	5.7	9.3	6.2
Ratio of viable to total ear number plant^{-1}	0.84	0.63	0.86	0.44

In the 2002–03 and 2003–04 wheat seasons the highest yield was obtained in the FNL treatment (Table 9) indicating that water management in the previous season was very important for the growth of the following crops. In the 2004–05 and 2005–06 wheat seasons the yield of ASL was significantly higher than that of ANL but not significantly different from that of AML or FNL (Table 9). This indicated that straw mulching could promote crop growth after a period of straw decomposition. Similar trends were observed for the results in 2004–05 and 2005–06.

TABLE 9. GRAIN YIELD (kg ha^{-1}) OF WHEAT OVER FOUR SEASONS

Treatment	2002–03	2003–04	2004–05	2005–06	Mean
FNL	4640 a	5348 a	4894 a	4571 ab	4863
ANL	3921 b	3043 c	4249 b	4153 b	3842
AML	4070 b	3332 c	4206 b	4891 a	4125
ASL	4074 b	3741 b	4503 ab	4534 ab	4213

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$.

3.1.4. Fate of applied urea as influenced by fertilizer, mulch and water management

The urea-N recovery by rice under FNL was 25% of applied N in 2002 and 21.6% in 2003 and N loss from the soil–plant system as determined by mass balance was 38.5% of applied N in 2002 and 45.6% in 2003 (Table 10). When the management was modified from FNL to ANL the recovery of fertilizer N by the rice crop did not change significantly, but soil residual fertilizer N decreased by 12.8% in 2002 and by 28.9% in 2003, which resulted in higher estimated fertilizer N losses of 60.4% in 2002 and 48.8% in 2003. When rice was grown under ASL, the fertilizer N recovery by the crop was significantly lower than that of ANL, as low as 21.9% in 2002, probably due to N immobilization of the decomposing straw competing for N. However, under non-flooded cultivation with plastic covering fertilizer N recovery by rice was the highest being 34.6% in 2002 and 27.0% in 2003 probably because the plastic covering enhanced the temperature and humidity of topsoil and promoted better growth and N uptake ability of the plants. The trends for the residual N and N losses were similar for the non-flooded treatments during both seasons (Table 10).

The urea-N recovery (41.3–46.4% of applied N) by wheat was the highest in FNL (Table 11) while the N loss (16.2–20.1% of applied N) was the lowest indicating that water management during the previous rice crop had a marked influence on N recovery and loss in the subsequent cropping season, probably due to the difference created in soil water status. Straw mulching wheat (accompanied with straw mulching non-flooded rice in the previous season) increased the soil residual fertilizer N and decreased N loss.

TABLE 10. RECOVERY (%) OF APPLIED UREA (180 kg N ha^{-1}) IN RICE AND SOIL OVER TWO SEASONS

Treatment	Year	Crop	Soil	Loss
FNL	2002	25.0 b	36.5 a	38.5 d
ANL		26.8 b	12.8 c	60.4 b
AML		34.6 a	14.2 c	51.2 c
ASL		21.9 c	12.2 c	65.9 ab
FNL	2003	21.6 c	33.8 a	45.6 c
ANL		22.3 bc	28.9 ab	48.8 bc
AML		27.0 a	21.3 b	51.7 a
ASL		24.2 bc	25.6 ab	50.2 ab

Data within a column and year followed by the same letter are not significantly different, DMRT at $P<0.05$.

TABLE 11. RECOVERY (%) OF APPLIED UREA (120 kg N ha^{-1}) IN WHEAT AND SOIL OVER TWO SEASONS

Treatment	Year	Crop	Soil	Loss
FNL	2002–03	41.3 a	38.6 a	20.1 e
ANL		36.5 b	31.3 bc	32.2 c
AML		33.1 bc	31.1 bc	35.9 b
ASL		37.9 b	33.7 b	28.5 d
FNL	2003–04	46.4 a	37.4 ab	16.2 d
ANL		35.0 b	40.9 a	24.1 c
AML		41.6 ab	32.2 b	26.2 bc
ASL		35.0 b	37.7 b	26.3 bc

Data within a column and season followed by the same letter are not significantly different, DMRT at $P<0.05$.

3.1.5. Water use efficiency of rice and wheat in relation to fertilizer, mulch and water management

The results show that water use efficiency (WUE) of rice is considerably lower than that of winter wheat (Tables 12 and 13). In the rice season the WUE of AML was not significantly different from that of ASL, except in 2003, and that FNL was not significantly different from ANL, except in 2004. This indicates that the flooded treatment and non-flooded without mulching resulted in lower WUE compared to non-flooded mulching (plastic or straw) treatments.

TABLE 12. WATER USE EFFICIENCY (kg m^{-3}) DURING FOUR RICE SEASONS

Treatment	2002	2003	2004	2005	Mean
FNL	1.27 ab	0.82 b	0.75 b	0.68 b	0.88
ANL	1.16 b	0.76 b	0.92 a	0.85 ab	0.92
AML	1.34 a	1.02 a	0.86 ab	0.91 a	1.03
ASL	1.22 ab	0.77 b	0.96 a	0.90 a	0.96

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$.

The following trend was observed in wheat: WUE was related to the water input from the previous cropping season. While the WUE of wheat was similar for the non-flooded treatments in the previous cropping season (AML, ANL and ASL), the WUE of these treatments was similar or lower than that in FNL.

TABLE 13. WATER USE EFFICIENCY (kg m^{-3}) DURING FOUR WHEAT SEASONS

Treatment	2002–03	2003–04	2004–05	2005–06	Mean
FNL	2.73 a	2.82a	1.45 a	0.95 ab	1.99
ANL	2.31 b	1.61 c	1.26 b	0.86 b	1.51
AML	2.39 b	1.76 bc	1.25 b	1.02 a	1.61
ASL	2.39 b	1.97 b	1.34 ab	0.94 ab	1.66

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$.

3.2. EXPERIMENT 2

3.2.1. Crop yield and nitrogen uptake in relation to form of applied fertilizer N

Both grain yield and total N uptake of rice in the FNL and ANL treatments were significantly lower with NO_3^- than NH_4^+ application (Table 14), indicating that NH_4^+ was preferably taken up by the rice crop. In the ASL treatment no significant differences in grain yield and N uptake were found between NH_4^+ and NO_3^- forms, possibly due to the N immobilization irrespective of the N form resulting from the straw decomposition. In the FNL treatment grain yield and total N uptake by wheat were significantly lower with NO_3^-

application compared to that with NH_4^+ (Table 15), indicating that NH_4^+ was probably the predominant N form in the soil and was preferentially taken up by wheat. By contrast there were no significant differences between N forms in the ANL and ASL treatments.

TABLE 14. GRAIN YIELD AND N UPTAKE OF RICE IN RELATION TO THE FORMS OF APPLIED FERTILIZER N

Treatment	Fertilizer N form	Grain yield (kg ha^{-1})	N uptake (kg ha^{-1})
FNL	NH_4^+	7735 a	156.3 a
	NO_3^-	7043 b	132.8 c
ANL	NH_4^+	7032 b	142.2 b
	NO_3^-	6756 c	136.7 bc
ASL	NH_4^+	6980 b	131.9 c
	NO_3^-	6831 bc	132.3 c

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$.

TABLE 15. GRAIN YIELD AND N UPTAKE BY WINTER WHEAT IN RELATION TO THE FORMS OF APPLIED FERTILIZER N

Treatment codes	Fertilizer N form	Grain yield (kg ha^{-1})	N uptake (kg ha^{-1})
FNL	NH_4^+	5608 a	119.3 a
	NO_3^-	5104 b	108.9 b
ANL	NH_4^+	5031 b	103.2 bc
	NO_3^-	5214 b	98.5 c
ASL	NH_4^+	5123 b	106.7 b
	NO_3^-	4916 b	105.4 b

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$.

3.2.2. Fate of types of fertilizer N in rice and wheat

Table 16 shows the fate of different types of fertilizer N (NH_4^+ or NO_3^- forms) in the rice season. Rice recovered significantly more NH_4^+-N than NO_3^--N under both flooded or non-flooded conditions, but there was no significant differences in soil residual NH_4^+-N, so that loss with NH_4^+-N was significantly lower than that of NO_3^--N. Conventionally flooded rice took up more N from NH_4^+ and NO_3^- than non-flooded rice, but soil residual N was similar, and thus the fertilizer N loss in flooded rice was less than that in non-flooded rice.

TABLE 16. RECOVERY (%) OF FERTILIZER N (180 kg N ha^{-1}) IN THE RICE SEASON

Treatment	Form of N	Crop	Soil	Loss
FNL	NH_4^+	34.4 a	35.6 a	30.0 c
	NO_3^-	24.5 b	30.4 ab	45.1 ab
ANL	NH_4^+	28.6 ab	28.9 b	42.5 b
	NO_3^-	25.6 b	25.4 b	49.0 a
ASL	NH_4^+	24.4 b	34.6 a	41.0 b
	NO_3^-	24.6 b	28.7 b	46.3 ab

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$.

In wheat the recovery of NH_4^+-N was significantly greater than NO_3^--N under both flooded or non-flooded conditions (Table 17).

TABLE 17. RECOVERY (%) OF FORMS OF FERTILIZER N (120 kg N ha^{-1}) IN THE WHEAT SEASON

Treatment	Form of N	Crop	Soil	Loss
FNL	NH_4^+	40.1 a	30.2 b	29.7 b
	NO_3^-	32.4 bc	28.6 b	39.0 a
ANL	NH_4^+	38.4 a	34.2 ab	27.4 b
	NO_3^-	33.3 bc	32.3 b	34.4 ab
ASL	NH_4^+	32.1 bc	38.9 a	29.0 b
	NO_3^-	28.3 c	36.7 a	35.0 ab

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$.

As residual NH_4^+-N in soil was similar to NO_3^--N, estimated N losses by mass balance were significantly lower with NH_4^+-N than NO_3^--N. Recovery of NH_4^+-N or NO_3^--N and soil residual N was not different between the flooded non-flooded treatments. Compared with the non-flooded only treatment, wheat recovered significantly less NH_4^+-N and NO_3^--N in the non-flooded straw mulching treatment, while the soil residual N with straw mulching was significantly higher than that of the flooded treatment, especially for NH_4^+-N.

4. CONCLUSIONS

Two field experiments were conducted on a purple earth soil in Wenjiang County, South-west China to investigate the effect of water regime and mulch and fertilizer N management on nitrogen and water use efficiencies of the rice–wheat cropping system.

In experiment 1, non-flooded rice cultivation with plastic mulching had similar effects on crop yield, N uptake, fertilizer N recovery and water use efficiency as conventionally flooded rice (without mulch). The rice grain yield decreased by approximately 10–15% in the non-flooded without mulch treatment, but wheat yields did not decrease significantly with straw mulching during the third and fourth years.

Urea-N recovery by flooded rice was on the average 22–25% of applied N and N losses were 39–45% of the applied N. Non-flooded cultivation did not significantly change the urea-N recovery, but significantly decreased the residual fertilizer N in the soil, resulting in an increased N loss. Non-flooded rice cultivation with straw mulching decreased urea-N recovery by rice but increased the soil residual fertilizer N, thus resulting in decreased N loss.

Urea-N recovery by wheat was on the average 37–44% of the applied N and N losses were 18–29% of the applied N. Non-flooded pre-treatment did influence the wheat fertilizer N recovery; less fertilizer N was recovered while soil N recovery was similar, thus resulting in higher N losses from the system compared to the flooded treatment. Water use efficiency for rice was much lower than that of winter wheat. The wheat water use efficiency was related to the water regime from the previous cropping season.

In experiment 2, regardless of flooding conditions, rice or wheat crops could recover significantly more NH_4^+-N than NO_3^--N, and the soil immobilized more NH_4^+-N than NO_3^--N. Therefore the loss with NH_4^+-N was significantly less than that of NO_3^--N. In the non-flooded straw mulching treatment, rice or wheat recovered significantly less N from NH_4^+-N or NO_3^--N, while the soil residual N was significantly higher than that of the flooded only treatment, especially for NH_4^+-N. Conventionally flooded rice took up more N from NH_4^+-N or NO_3^--N than non-flooded rice, while recovery of NH_4^+-N or NO_3^--N and soil residual N in the wheat season were not different between flooded and non-flooded treatments.

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INTEGRATED WATER AND NITROGEN MANAGEMENT FOR RICE CULTIVATED IN AEROBIC AND WATERLOGGED SOIL CONDITIONS IN CHINA

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Abstract

A field experiment was carried out over 4 years (2002–06) at Nanjing, (33°27'N, 120°11'E), Jiangsu province, China to study the effect of rice cultivated in an aerobic soil with mulching on yield, nitrogen use efficiency (NUE), and water use efficiency (WUE) of a rice-barley rotation. The experiment consisted of three treatments: i) rice grown in aerobic soil covered with transparent plastic film (AML), ii) rice grown in aerobic soil mulched with pre-composted rice straw (ASL), and iii) rice grown in puddled waterlogged soil (traditional practice, FNL). Generally, both grain yield and straw dry matter of rice were significantly higher in ASL than in the other two treatments, and the average grain yield of barley was also higher in the ASL treatment. On the basis of total water input (grain yield / rainfall + irrigation) and total biomass (total biomass / rainfall + irrigation), water use efficiency (WUE) in rice was about three times greater in ASL and AML compared to the FNL treatment. However, based only on irrigation water, WUE (grain yield / irrigation, and total biomass / irrigation) was ten times higher in ASL and AML than in the FNL treatment. There were no significant differences in average WUE between different treatments in the barley crop. Apparent fertilizer N recovery (AR) of rice, averaged over the four years, was 32, 30 and 35% in FNL, AML and ASL, respectively. The AR for barley was in the following order: ASL>AML>FNL. ^{15}N fertilizer recovery was 21.0–33.4% in rice and 17–35.4% in barley. Total NUE of the rotation system (rice and barley) was 50.1, 52.0 and 51.5% in FNL, AML and ASL, respectively. The barley recovered 0.5–2.4% from the residual ^{15}N fertilizer applied to the previous rice crop. The results demonstrate that cultivation in aerobic soil with mulching as in the AML and ASL treatments could be applied to the rice–barley rotation systems in Jiangsu province, China.

1. INTRODUCTION

Rice is one of the three most important cereal crops (rice, wheat and maize) grown in China and it accounts for 40% of the summer crops, with about 40 million hectares (ha) cultivated per year. Waterlogging is the traditional cultivation practice of rice. More than 80% of the irrigation water used for agriculture in China is employed for rice production [1]. Supplementary irrigation water is applied according to the rainfall regime of the production areas. For instance in Jiangsu province, which receives 800–1000 mm precipitation annually, some 10 500–15 000 m^3 of irrigation water ha^{-1} are still applied per rice growing season and more irrigation water is needed in the low rainfall areas. Therefore, much work has been undertaken to save water in rice cultivation. For instance, it was found that intermittent irrigation can save 20–60% of irrigation water when compared with traditional waterlogged cultivation, the actual amount of irrigation water saved depending on the rainfall in different areas [2, 3]. However, intermittent irrigation of rice is still a form of waterlogged cultivation because the rice crop still requires waterlogged conditions at particular growth stages.

The cultivation of rice in aerobic soil is a complete innovative cultivation system that shows great potential for water savings in agriculture, especially in the areas that receive more than 800 mm of precipitation annually. The rice (not upland varieties but paddy rice, once traditionally grown in waterlogged soil with high yield) is grown in a soil with the water content between 60–90% of the water holding capacity (WHC). In Jiangsu province, for example, a rice grain yield of 8.74 t ha^{-1} could be obtained in aerobic cultivation with only 11% yield reduction compared to that in waterlogged cultivation with the same rice cultivar [4, 5]. About 100–150% of the irrigation water could be saved by the aerobic system, compared with waterlogged cultivation and the resulting 11% reduction in grain yield of rice is small in relation to the gains of the irrigation water saved.

Irrigated rice in China accounts for nearly 30% of global rice production and about 7% of global N consumption [6]. The low agronomic N use efficiency (ANUE, kg grain yield increase per kg N applied) of this system has become a serious threat to the environment due to the high risk for N losses and related problems. There is great scope for enhancing crop yields through improving the use efficiency of both water (WUE) and nitrogen (NUE) inputs.

Although there have been many studies on rice cultivated in aerobic soil, the NUE in this cultivation system is still poorly understood, especially the effects on the subsequent crop. The objectives of this study were, therefore, to evaluate the effects of aerobic (unsaturated) and waterlogged cultivation on crop yield, NUE and WUE of a rice–barley rotation. The ^{15}N isotopic technique was used to determine the NUE of the rice–barley system, in particular fertilizer N recovery in the crops and soil and to estimate the fertilizer ^{15}N losses from the soil–plant system by mass balance.

2. MATERIALS AND METHODS

2.1. EXPERIMENTAL SITE

The field experiments were conducted during the period 2002–06 at the farm of the Yancheng Agricultural Institute, Nanjing (33°27’N, 120°11’E), Jiangsu province, China. The soil was an aqualkalic Halosol with a sandy loam texture and a pH in water of 8.3. The concentrations of organic C and total N in the 0–20 cm topsoil layer were 12.5 and 0.84 g kg^{-1}, respectively, at the beginning of the experiment.

2.2. CLIMATIC CONDITIONS

Mean monthly precipitation data (Fig.1) were variable throughout the five years of experimentation with a rainy period extending from June through September. Mean monthly minimum and maximum temperatures and long term average values are shown in Fig. 2A and Fig 2B, respectively.

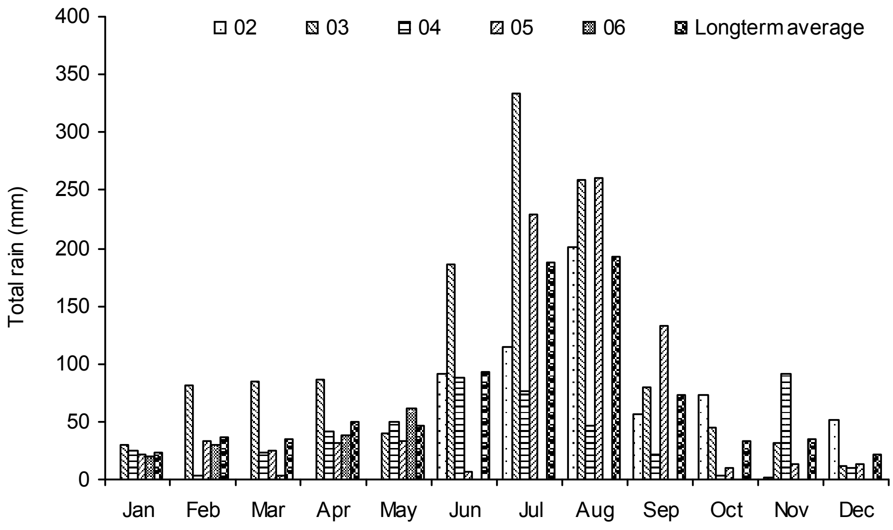
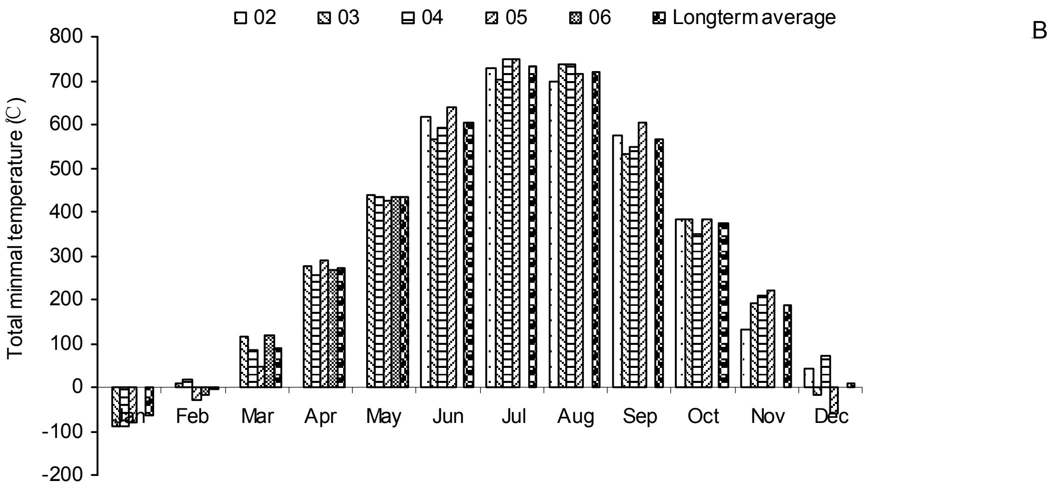


FIG. 1. Monthly rainfall at the experimental site.



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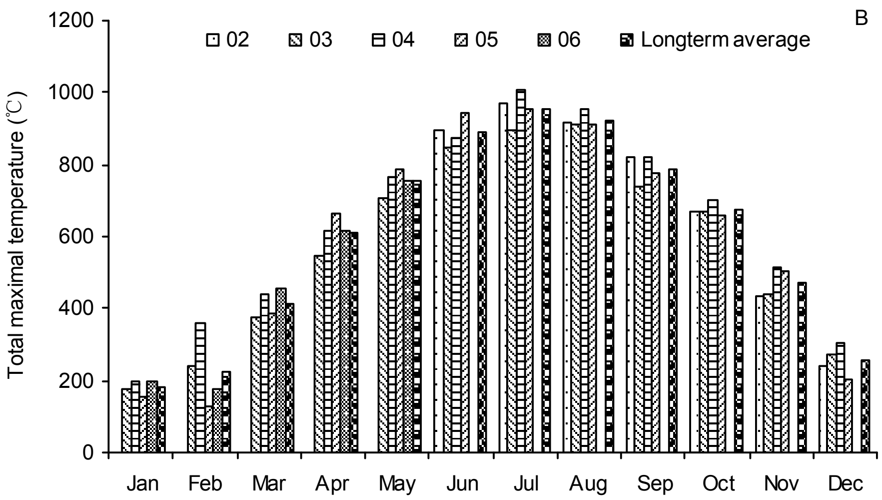

FIG. 2. Mean monthly temperatures at the experimental site, A: minimum temperature; B: maximum temperature.

2.3. EXPERIMENTAL DESIGN AND TREATMENTS

The experiment consisted of three treatments: i) rice grown in aerobic soil covered with transparent plastic film (AML), ii) rice grown in aerobic soil mulched with pre-composted rice straw (ASL), and iii) rice grown in puddled waterlogged soil (traditional practice, FNL). Each plot was 6 x 12 m. Three replicates of the waterlogged rice treatment were located in an isolated waterlogged block while three replicates of both water saving treatments were arranged at random in an isolated aerobic block (Fig. 3). Subplots, each 0.9 m^2 (0.75 × 1.2 m), were set up in each plot of the three treatments for an ^{15}N isotopic study during the rice and barley growing seasons. Plastic frames with dimensions of 120 (length) x 75 (width) × 40 cm (height) formed the boundaries of the subplots. The frames were inserted into the soil leaving 5 cm above the soil surface. ^{15}N labelled urea (5 atom % ^{15}N) was applied at 180 kg N ha^{-1} to the subplots in the same manner as in the main plots. The management practices used in the ^{15}N experiment including application method and rate was the same as in the main plots. Soil and plant samples were taken at physiological maturity and analysed for total N and ^{15}N abundance. In addition, residual effects of applied urea-N were investigated in subsequent cropping seasons.

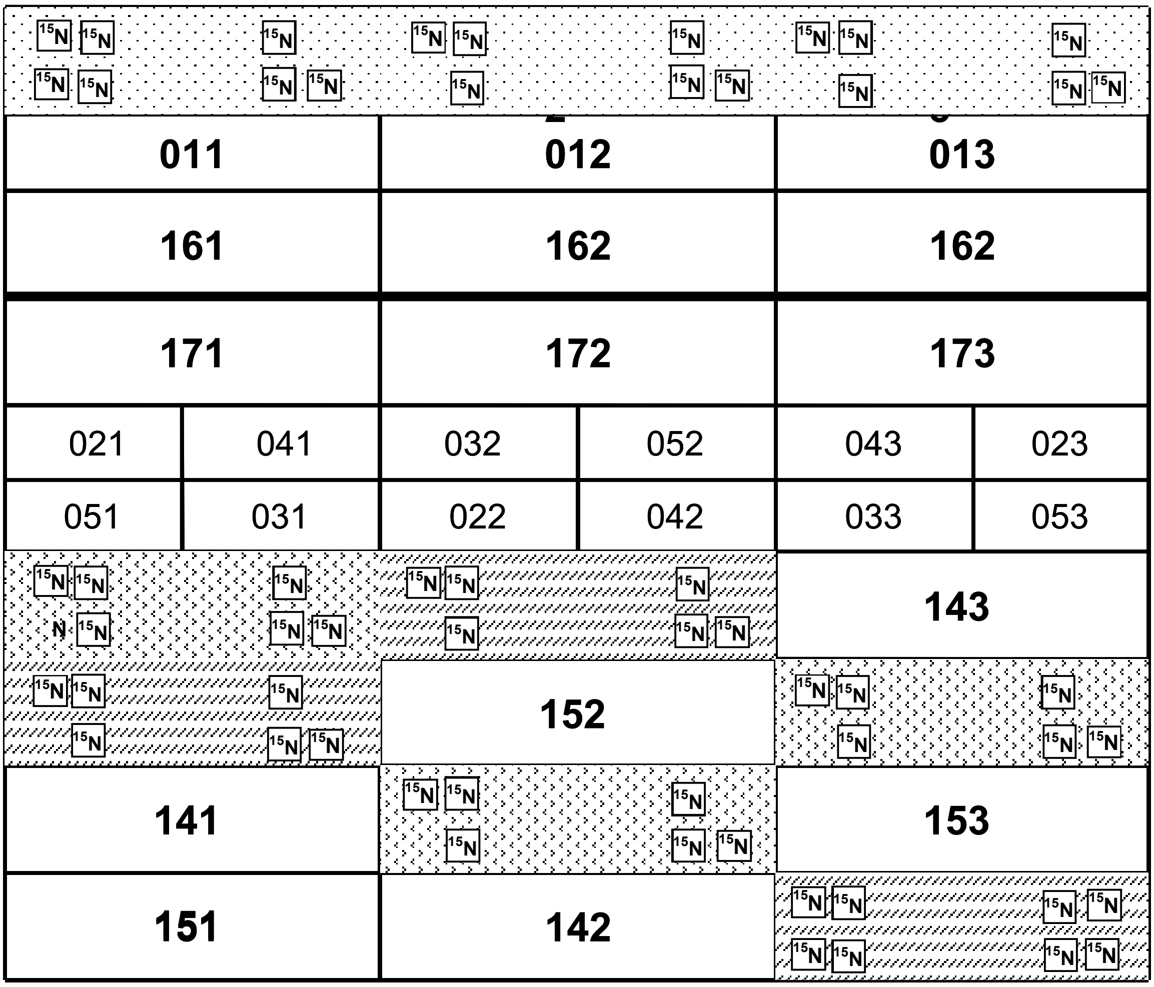

FIG. 3. Plan of the entire experimental plot. 11x – rice cultivated in waterlogged field; 12x – rice cultivated in aerobic soil with plastic film mulching; 13x – rice cultivated in aerobic soil with straw mulching. 0xx– without nitrogen fertilizer. The ^{15}N subplot on the left of each plot was set up during the rice season, while the subplot on the right was set up in the barley season.

2.4. FIELD AND CROP MANAGEMENT

The hybrid rice cultivar Teyou 559, popular in the area for many years, was used in 2002 and 2003. All water saving plots were seeded in aerobic soil on May 10 and transplanted on June 13 in these two years. The second variety, a high yield hybrid rice variety, Xianyou 63, was selected for 2004 and 2005 and it was transplanted on June 14. Pre-composted rice straw was mulched onto the soil surface at a rate of 6000 kg ha^{-1} in the straw-mulch treatment. In the plastic film plots the plastic was spread on the soil surface and holes cut to allow for rice plant emergence from the film. The water content of the 0–20 cm soil layer in the aerobic plots was maintained near 80% WHC by using a series of tensiometers during the rice growing period. In the traditional waterlogged cultivation, a 5 cm layer was maintained until flowering, except for a one week drainage period at the end of effective tillering, followed by intermittent irrigation. All plots received 90 kg ha^{-1} of P and K broadcast on the surface of the aerobic plots prior to sowing, or broadcast and incorporated at puddling.

Nitrogen fertilizer was applied as urea at 180 kg N ha^{-1} with 30% as basal fertilizer, 40% top-dressed at tillering and 30% at the booting stage.

Gangpi No. 2 barley was sown into the above plots in October after the rice harvest. All plots received 60 kg P ha^{-1} and 90 kg k ha^{-1} broadcast on the soil surface prior to sowing. N fertilizer was applied as urea at 120 kg N ha^{-1} with 40% as basal fertilizer, 40% top-dressed at tillering and 20% at the booting stage.

2.5. SOIL SAMPLING AND ANALYSES

Soil samples were taken periodically during the barley and rice growing seasons with an auger. For each plot, seven soil cores were taken to 80 cm depth and divided into increment depths of 0–20, 20–40, 40–60 and 60–80 cm. The samples from the seven cores within a depth in each plot were mixed thoroughly and placed in a plastic bag. The samples were then transported to the laboratory for immediate extraction for mineral N analysis, or stored in a refrigerator at 4°C for less than 24 h until analysis. A subsample of each soil sample was oven dried at 105°C to determine gravimetric water content and to calculate the oven dry weight of the soil sample.

A 30-g field moist soil sample was extracted with 100 ml 0.01 M KCl by shaking the suspension for 1 h, followed by filtration. The filtrate was frozen until analysis. Extractable NH_4^+-N and NO_3^--N concentrations were determined using a Continuous Flow Auto Analyser (AA3, Bran & Luebbe).

2.6. PLANT BIOMASS SAMPLING AND MEASUREMENTS

Barley and rice plants were periodically sampled from barley emergence or rice transplanting until maturity. All plants within a 0.5 m^2 rectangle were cut at ground level and the dry weight was measured after drying at 70°C for 72 h. A distance of at least 1 m was left between successive sampling areas. The plants were sampled from a 2 × 3 m area at the final harvest and the ears from each plant were threshed by a stationary thresher. The dry weights of grain and a subsample of straw were determined after drying at 70°C for 72 h.

For plant total N analysis, the replicated plant samples per plot were pooled to give one composite sample per plot. These composite samples were ground in a laboratory mill (0.5–mm screen) and their N concentration determined by the salicylic-acid/thiosulfate modification of the Kjeldhal method.

2.7. EVALUATION PARAMETERS

Water use efficiency (WUE) was estimated in two ways. Considering the crop production (grain yield and total biomass) and water inputs (rainfall + irrigation) as follows:

WUE (kg m^{-3}) = Grain yield / total water inputs (irrigation + rainfall)

or WUE (kg m^{-3}) = Total biomass / total water inputs (irrigation + rainfall)

Rice WUE was also calculated using irrigation inputs only whereas barley WUE was obtained using rainfall inputs.

The following parameters were calculated using the equations below for evaluating NUE [1, 7, 8, 9]:

Physiological N use efficiency (PNUE) = Grain yield / Total N uptake

Agronomic N use efficiency (ANUE) = (Grain yield with N application – Grain yield from zero N plots) / N applied

For the difference method, apparent recovery of the fertilizer N was calculated as follows:

Apparent recovery of applied fertilizer N (AR) = (N uptake with N application – N uptake from zero N plots) / N applied

For the isotopic method the $\%^{15}N$ abundance in rice and barley grain and straw at harvest time were measured by isotope ratio mass spectrometry at the IAEA's Seibersdorf laboratory. Also ^{15}N remaining in the soil samples collected to a depth of 40 cm were determined at the end of each crop.

% Nitrogen derived from fertilizer (%Ndff) = atom $\%^{15}N$ excess (plant) / atom $\%^{15}N$ excess (fertilizer) × 100

% Fertilizer nitrogen use efficiency (% FNUE) = N fertilizer yield (kg ha^{-1}) / N fertilizer rate (kg ha^{-1}) × 100

N fertilizer yield (kg N ha^{-1}) = {Grain dry matter (kg ha^{-1}) x grain N (g kg^{-1}) x %Ndff / 100} + {straw dry matter (kg ha^{-1}) × straw N (g kg^{-1}) × % Ndff / 100}

With these data total fertilizer nitrogen recoveries (soil and plant) during each cropping season were determined. The residual fertilizer N recovered by the subsequent barley and rice crops were also determined in plant samples.

2.8. STATISTICAL ANALYSES

Statistical analyses were conducted using SPSS v. 11.5. Differences among the treatments means were evaluated with the Duncan Multiple Range Test (DMRT) at $P<0.05$.

3. RESULTS AND DISCUSSION

3.1. SOIL MINERAL N DURING THE RICE AND BARLEY GROWING SEASONS

3.1.1. Soil NH_4^+-N in the rice season

Although the NH_4^+ concentration varied between the layers from 0–20, 20–40, 40–60 to 60–80 cm depth, there were no significant differences between treatments. The NH_4^+-N concentration in the different soil layers ranged from 0.4–11.9 mg kg^{-1} at rice tillering and from 0.7–11.9 mg kg^{-1} at maturity (Tables 1–4). The NH_4^+ concentration varied with both treatment and years. Irregular fluctuations in the NH_4^+ concentration occurred in all layers up to 80 cm depth. Rice cultivation method significantly affected soil NH_4^+ concentration. Paddy cultivation of rice maintained, on average, higher concentrations of NH_4^+ in the 0–20 cm soil layer compared to the aerobic soil, although the same amount of N fertilizer had been applied (Tables 1–4). This was due to most of the applied N fertilizer being converted to NO_3^- in the aerobic soil (Tables 5–8). In 2003, NH_4^+ concentrations in all layers from 0–80 cm were higher than in the other three years, which were probably due to the N fertilization practices.

3.1.2. Soil NH_4^+-N in the barley season

NH_4^+-N concentrations in the soil ranged from 0.5–5.5 mg kg^{-1} during the barley vegetative period during 2003–06 (Tables 1–4). The cultivation method in the preceding rice crop affected the NH_4^+-N concentration in the in 0–20 cm soil layer in the barley crop. The

NH_4^+-N concentration in the barley soil at jointing was higher when it followed paddy than following aerobic cultivation (Table 1). This may be due to the higher soil water content in the paddy treatment.

TABLE 1. AMMONIUM-N (mg kg^{-1}) IN THE 0–20 cm SOIL LAYER AT RICE TILLERING, AT BARLEY JOINTING AND AT MATURITY OF BOTH CROPS OVER FOUR YEARS

Treatment	NH_4^+-N at rice tillering					NH_4^+-N at barley jointing				
	2002	2003	2004	2005	Mean	2002	2003	2004	2005	Mean
FNL	0.7	8.3	5.4	5.7	5.0	2.1	1.9	2.0	2.4	2.1
AML	0.4	9.6	1.3	4.7	4.0	2.0	1.9	1.3	2.0	1.8
ASL	0.7	7.7	0.7	4.9	3.5	2.2	2.0	1.5	2.6	2.0
Mean	0.6	8.6	2.5	5.1	4.2	2.1	2.0	1.6	2.4	2.0
Lsd ($P<0.05$)	0.1	1.4	0.6	1.2	0.6	0.8	0.5	0.4	0.3	0.4
Treatment	NH_4^+-N at rice maturity					NH_4^+-N at barley maturity				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	1.2	4.7	9.0	1.4	4.0	2.5	2.9	1.2	1.0	1.9
AML	0.7	4.4	7.0	2.5	3.7	2.6	2.8	0.9	1.0	1.8
ASL	0.8	4.3	8.1	1.7	3.7	1.8	3.9	0.9	1.2	1.9
Mean	0.9	4.5	8.0	1.9	3.8	2.3	3.2	1.0	1.0	1.9
Lsd ($P<0.05$)	0.3	1.1	1.8	0.7	0.7	0.8	0.6	0.5	0.7	0.3

TABLE 2. AMMONIUM-N (mg kg^{-1}) IN THE 20–40 cm SOIL LAYER AT RICE TILLERING AT BARLEY JOINTING AND AT MATURITY OF BOTH CROPS OVER FOUR YEARS

Treatment	NH4+-N at rice tillering					NH4+-N at barley jointing				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	0.4	8.3	4.0	4.9	4.4	1.7	1.8	1.5	1.7	1.7
AML	0.4	10.0	1.1	4.3	4.0	1.7	1.4	1.6	1.6	1.6
ASL	1.1	9.2	1.1	4.7	4.0	1.7	0.6	1.0	1.4	1.2
Mean	0.6	9.0	2.0	4.6	4.2	1.7	1.3	1.4	1.6	1.5
Lsd (P<0.05)	0.3	1.3	0.7	0.7	0.5	0.6	0.4	0.3	0.4	0.2
Treatment	NH4+-N at rice maturity					NH4+-N at barley maturity				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	2.1	4.8	7.3	1.9	4.0	5.1	2.9	0.9	1.0	2.5
AML	1.5	4.8	8.2	2.0	4.1	1.9	2.7	0.7	0.5	1.5
ASL	1.5	4.7	11.9	2.3	5.1	2.3	4.1	0.7	0.7	2.0
Mean	1.7	4.8	9.1	2.0	4.4	3.1	3.2	0.8	0.7	2.0
Lsd (P<0.05)	0.5	1.5	1.0	0.7	0.5	1.9	0.8	0.5	0.3	0.4

TABLE 3. AMMONIUM-N (mg kg^{-1}) IN THE 40–60 cm SOIL LAYER AT RICE TILLERING, AT BARLEY JOINTING AND AT MATURITY OF BOTH CROPS OVER FOUR YEARS

Treatment	NH4+-N at rice tillering					NH4+-N at barley jointing				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	0.9	9.1	4.4	4.3	4.7	3.1	1.3	2.0	1.1	1.9
AML	0.5	10.6	0.9	3.7	3.9	2.2	1.1	1.5	0.7	1.4
ASL	0.9	10.4	2.5	3.7	4.4	2.1	0.9	1.7	0.9	1.4
Mean	0.8	10.0	2.6	3.9	4.3	2.5	1.1	1.8	0.9	1.6
Lsd ($P<0.05$)	0.3	2.0	0.4	1.2	0.5	0.5	0.4	0.4	0.5	0.2
Treatment	**NH4+-N at rice maturity**					**NH4+-N at barley maturity**				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	1.4	4.2	7.5	1.6	3.7	1.5	2.8	1.1	0.5	1.5
AML	1.3	3.9	7.7	1.8	3.7	5.5	2.9	0.6	0.7	2.5
ASL	1.2	4.3	7.6	1.9	3.8	2.5	3.5	0.6	0.8	1.9
Mean	1.3	4.2	7.6	1.8	3.7	3.1	3.0	0.8	0.7	1.9
Lsd ($P<0.05$)	0.3	0.6	0.6	0.6	0.4	1.0	1.4	0.4	0.2	0.5

TABLE 4. AMMONIUM-N (mg kg^{-1}) IN THE 60–80 cm SOIL LAYER AT RICE TILLERING AT BARLEY JOINTING AND AT MATURITY OF BOTH CROPS OVER FOUR YEARS

Treatment	NH_4^+-N at rice tillering					NH_4^+-N at barley jointing				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	2.6	10.0	3.3	3.6	4.9	1.8	2.4	2.4	0.9	1.9
AML	1.9	10.6	1.9	3.5	4.5	2.4	1.5	2.7	0.9	1.9
ASL	2.0	11.1	1.2	2.7	4.3	2.7	1.6	2.2	1.1	1.9
Mean	2.1	10.6	2.1	3.3	4.6	2.3	1.8	2.4	1.0	1.9
Lsd (P<0.05)	0.7	2.3	0.5	0.9	0.6	0.7	0.5	1.1	0.6	0.4
Treatment	**NH_4^+-N at rice maturity**					**NH_4^+-N at barley maturity**				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	1.0	3.9	7.8	1.5	3.6	1.6	3.3	0.8	0.6	1.6
AML	1.3	4.3	7.9	1.5	3.8	4.8	3.4	0.6	0.8	2.4
ASL	0.7	4.3	8.6	2.0	3.9	2.6	3.6	0.5	0.7	1.9
Mean	1.0	4.2	8.0	1.6	3.7	3.0	3.50	0.6	0.7	2.0
Lsd (P<0.05)	0.5	0.9	1.0	0.4	0.3	1.0	1.0	0.2	0.3	0.4

3.1.3. Soil NO_3^--N in the rice season

The NO_3^- concentration in the different soil layers ranged from 0.5–18.7 mg kg^{-1} at rice tillering stage and 0.5–20.5 mg kg^{-1} at maturity (Tables 5–8). Nitrate concentrations in the soil profile were highly variable during the four year period. Averaged over the four years the 0–20 cm soil layer in the aerobic rice soil contained more NO_3^--N (11.4 mg kg^{-1}) than the paddy soil (4.6 mg kg^{-1}) at tillering. The NO^-_3 concentration at maturity was lower than at tillering in the aerobic soil treatment. This difference may be due to the influence of rice N uptake. Regardless of the rice cultivation treatment NO_3^--N decreased with soil depth (Tables 5–8). This suggests that the risk of nitrate leaching is low, even though the rice was cultivated in an aerobic soil.

TABLE 5. NITRATE-N (mg kg^{-1}) IN THE 0–20 cm SOIL LAYER AT RICE TILLERING, AT BARLEY JOINTING AND AT MATURITY OF BOTH CROPS OVER FOUR YEARS

Treatment	NO_3^--N at rice tillering					NO_3^--N at barley jointing				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	6.5	5.4	2.6	4.1	4.6	15.2	40.4	2.7	2.0	15.1
AML	18.7	6.3	15.3	5.6	11.5	12.3	76.0	3.8	1.9	23.5
ASL	15.7	7.9	16.2	6.0	11.4	5.7	75.9	5.5	2.3	22.3
Mean	13.6	6.5	11.3	5.2	9.2	11.0	64.1	4.0	2.1	20.3
Lsd (P<0.05)	2.4	1.8	2.3	1.3	1.2	1.9	11.5	1.4	0.7	3.3
Treatment	**NO_3^--N at rice maturity**					**NO_3^--N at barley maturity**				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	2.0	7.5	8.7	6.7	6.3	2.1	7.5	3.2	6.4	4.8
AML	3.3	6.9	13.6	4.9	7.1	2.2	12.1	4.6	5.4	6.0
ASL	3.5	9.2	20.4	6.8	10.0	2.3	11.5	6.0	8.3	7.0
Mean	3.0	7.9	14.2	6.1	7.8	2.2	10.3	4.6	6.7	6.0
Lsd (P<0.05)	0.5	1.5	1.72	0.9	0.6	0.7	2.0	0.8	1.4	0.5

3.1.4. Soil NO_3^--N in the barley season

The NO_3^--N concentration was higher than NH_4^+-N and ranged from 0.5–76 mg kg^{-1} in the soil profile during the barley growing period (Tables 5–8). The preceding rice cultivation method also affected NO_3^--N concentration in 0–20 cm soil layer with it being lower in the plots where rice had been cultivated in paddy. The NO_3^--N concentration in the 0–20 cm soil layer was higher than that in the 20–80 cm soil layers, indicating low leaching of nitrate during the barley growing season.

TABLE 6. NITRATE-N (mg kg^{-1}) IN THE 20–40 cm SOIL LAYER AT RICE TILLERING AT BARLEY JOINTING, AND AT MATURITY OF BOTH CROPS OVER FOUR YEARS

Treatment	NO_3^--N at rice tillering					NO_3^--N at barley jointing				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	5.5	5.4	6.3	3.5	5.2	4.5	5.5	1.7	1.7	3.3
AML	7.7	5.6	11.3	4.0	7.2	4.2	3.7	2.7	1.9	3.1
ASL	9.3	5.9	15.6	4.2	8.7	3.4	4.8	3.2	2.4	3.5
Mean	7.5	5.6	11.1	3.9	7.0	4.0	4.7	2.6	2.0	3.3
Lsd *(P*<0.05)	1.0	0.9	1.6	0.7	0.5	0.9	1.0	0.7	1.0	0.2
Treatment	NO_3^--N at rice maturity					NO_3^--N at barley maturity				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	1.6	3.1	4.9	5.0	3.7	1.6	5.4	3.1	3.6	3.4
AML	2.2	3.2	8.4	4.2	4.5	2.1	7.9	3.7	5.0	4.7
ASL	2.6	3.7	16.9	4.8	7.0	1.8	6.3	2.6	5.8	4.1
Mean	2.1	3.4	10.0	4.7	5.0	1.9	6.5	3.1	4.8	4.0
Lsd (*P*<0.05)	0.8	0.7	2.0	1.6	0.3	0.5	1.3	1.0	0.9	0.4

TABLE 7. NITRATE-N (mg kg^{-1}) IN THE 40–60 cm SOIL LAYER AT RICE TILLERING, AT BARLEY JOINTING AND AT MATURITY OF BOTH CROPS OVER FOUR YEARS

Treatment	NO_3^--N at rice tillering					NO_3^--N at barley jointing				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	0.5	3.0	3.5	3.7	2.7	2.3	2.0	0.9	1.5	1.7
AML	1.6	3.6	9.5	3.4	4.5	1.1	3.0	1.2	1.9	1.8
ASL	3.0	4.3	14.7	2.7	6.2	0.9	2.6	1.4	1.4	1.6
Mean	1.7	3.7	9.2	3.3	4.5	1.4	2.5	1.2	1.6	1.7
Lsd (*P*<0.05)	1.1	1.1	1.0	0.8	0.6	0.6	0.7	0.5	0.7	0.3
Treatment	NO_3^--N at rice maturity					NO_3^--N at barley maturity				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	0.6	2.6	3.9	3.6	2.7	1.3	2.4	0.6	2.3	1.7
AML	1.7	2.5	5.4	3.2	3.2	1.0	6.1	0.5	3.2	2.7
ASL	1.6	2.3	9.2	2.6	4.0	0.5	4.7	0.5	2.5	2.0
Mean	1.3	2.5	6.2	3.1	3.3	0.9	4.4	0.5	2.7	2.1
Lsd (*P*<0.05)	0.5	0.9	0.9	0.9	0.6	0.3	1.0	0.1	0.8	0.4

3.2. BIOMASS ACCUMULATION OF RICE AND BARLEY

3.2.1. Biomass accumulation in rice

The biomass of rice was strongly influenced by aerobic mulching cultivation (Fig. 4). In 2003, total biomass accumulation in AML and ASL was maintained at similar rates and was higher than in FNL from transplanting to booting (85 DAT) (Fig. 4). This was mainly because the rice plants produced more tillers in aerobic conditions than in paddy cultivation. It has been demonstrated that a higher tiller number significantly increased the leaf area index and consequently the radiation interception capacity which resulted in a higher biomass production [10]. However the dry matter accumulation rate slowed down in the plastic film mulching treatment after booting (Fig. 4, 80 DAT). In both aerobic soil mulching treatments, the biomass accumulation was greater in ASL than in AML after filling (100 DAT).

TABLE 8. NITRATE-N (mg kg^{-1}) IN THE 60–80 cm SOIL LAYER AT RICE TILLERING, AT BARLEY JOINTING AND AT MATURITY OF BOTH CROPS OVER FOUR YEARS

Treatment	NO_3^--N at rice tillering					NO_3^--N at barley jointing				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	0.9	2.0	2.9	2.3	2.0	0.5	2.6	0.7	1.3	1.3
AML	1.8	3.0	6.0	2.4	3.3	0.9	5.0	0.7	1.4	2.0
ASL	1.8	2.7	4.9	1.7	2.8	0.5	1.9	1.0	1.1	1.1
Mean	1.5	2.6	4.6	2.1	2.7	0.6	3.1	0.8	1.3	1.5
Lsd (P<0.05)	0.5	0.7	1.1	0.7	0.5	0.6	0.9	0.3	0.4	0.3
Treatment	NO_3^--N at rice maturity					NO_3^--N at barley maturity				
	2002	2003	2004	2005	Mean	2003	2004	2005	2006	Mean
FNL	0.5	1.5	2.8	1.7	1.6	1.4	1.5	0.5	1.2	1.1
AML	1.9	1.8	3.3	1.7	2.2	0.5	2.6	0.8	2.0	1.5
ASL	1.8	2.2	3.7	1.5	2.3	0.4	1.7	0.5	1.6	1.0
Mean	1.4	1.9	3.3	1.7	2.0	0.8	1.9	0.6	1.6	1.2
Lsd (P<0.05)	0.3	0.7	1.0	0.7	0.4	0.3	0.6	0.4	0.5	0.3

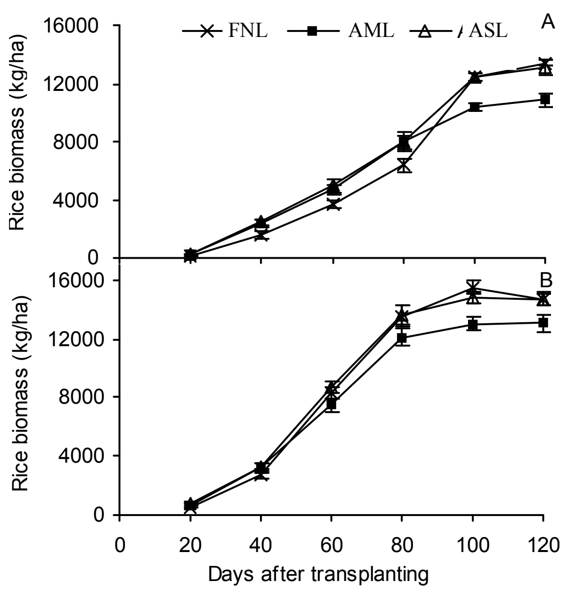

FIG. 4. Biomass accumulation in rice plants in 2003 (A) and 2004 (B). Bars represent the Lsd (P<0.05)

Total biomass accumulation (Fig. 4) was greater in 2004 than in 2003 across all treatments, possibly due to the change in rice variety in 2004, and the higher solar radiation and temperatures in 2004 than in 2003 (Fig. 2). The trend in biomass accumulation in the different treatments at maturity in 2004 followed the same pattern as in 2003, being FNL≥ ASL>AML.

3.2.2. Biomass accumulation in barley

Dry matter accumulation in barley plants was similar in 2004 and 2005 in spite of the different previous rice cultivation systems (Fig. 5). In both years the biomass of barley plants cultivated in previously waterlogged soil was slightly less than that grown in previous aerobic soil (Fig. 5). The biomass of barley plants was lower in all treatment in 2005 than in 2004 during 90–150 days after sowing, which was related to the low temperature during this time in 2004.

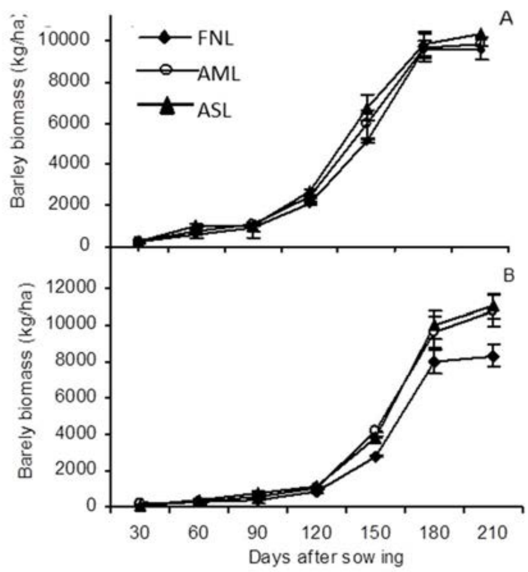

FIG. 5. Biomass accumulation in barley plants in 2004 (A) and 2005 (B). Bars represent the Lsd (P<0.05).

3.3. GRAIN YIELD OF RICE AND BARLEY

The average grain yields of rice and barley from 2001–05 were significantly affected by the cultivation system (Table 9). The average grain yields of rice were higher in FNL and ASL than in AML. There were no significant differences in rice yields between FNL and ASL. However, the average straw yield of rice in the ASL treatment was higher than the other two treatments, and AML had the lowest straw yield. Compared with aerobic conditions, the average total biomass (grain + straw) of rice was higher in ASL than in the FNL treatment, and this difference was predominantly due to the increased straw dry matter yield, which resulted in a lower harvest index in ASL than in the FNL treatment. Average total biomass (grain + straw) was about 20% higher in ASL than in the AML treatment, but the calculated harvest index was lower in ASL than in the AML treatment. This would suggest that the implementation of a study on the translocation of photo assimilates as affected by the experimental treatments would be rewarding.

The average grain yields of barley were higher in the ASL treatment than in the other two treatments (Table 9). There were no significant differences between the FNL and AML treatments. The average straw dry matter of barley was higher in ASL than in the AML and FNL treatments, and the AML treatment had a higher barley straw dry matter than FNL averaged over the five years.

TABLE 9. AVERAGE GRAIN AND STRAW YIELD (kg ha^{-1}) OF RICE AND BARLEY OVER FIVE YEARS FROM 2001–05

Treatment	Rice yield		Barley yield	
	Grain	Straw	Grain	Straw
FNL	6623 a	5141 a	4222 b	4969 b
AML	6108 b	4731 b	4286 b	5214 b
ASL	6618 a	5617 a	4704 a	5856 a

Data within a column followed by the same letter are not significantly different, DMRT at P <0.05

Generally, both grain and straw dry matter yield of rice was significantly higher in ASL than in the other two treatments (Fig. 6A and Fig. 6B). Rice grain yield in the FNL treatment differed significantly between the five years whereas in the AML treatment, rice grain yield remained constant (Fig. 6A). In 2005, the highest rice grain yields were observed in the aerobic soil mulched with pre composted rice straw (ASL), which produced a higher yield compared with the waterlogged and aerobic soil mulched with plastic film.

Similar patterns for rice straw dry matter are shown in Fig. 6B. Rice straw dry matter yield was consistently higher in ASL than in the FNL and AML treatments and was significantly different between years in the FNL treatment. In 2003, rice straw dry matter was low in all treatments and lowest in the FNL treatment. This is possibly related to the higher rainfall (744 mm) of this year. This effect may likely indicate that rice plants grew better when they were exposed to water stress during their early growth. In 2005, rice straw dry matter in the ASL treatment was significantly higher than that of FNL and AML treatments. Straw dry matter yield was higher in 2004 and 2005 than in 2002 and 2003 most likely due to the rice variety being changed from Teyou 559 to Xianyou 63.

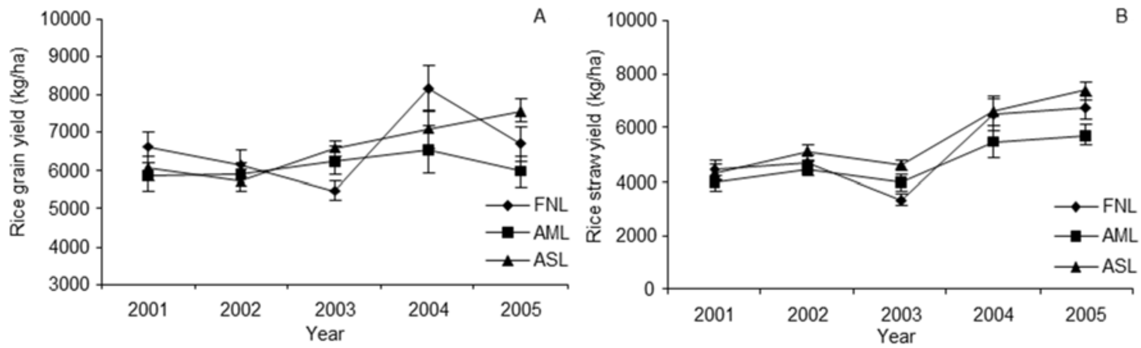

FIG.6. Grain yield (A) and straw dry matter (B) of rice in the 5–year experiment carried out in Yancheng, Jiangsu province, China from 2001–05. Bars represent the Lsd (P<0.05).

Generally, barley grain yield was slightly higher in ASL than in the FNL and AML treatments (Fig. 7A). In 2003 there were no differences between treatments whereas in 2004 barley grain yield was higher in ASL and AML than in the FNL treatment. In 2005 yields were higher in FNL and ASL than in the AML treatment (Fig. 7A).

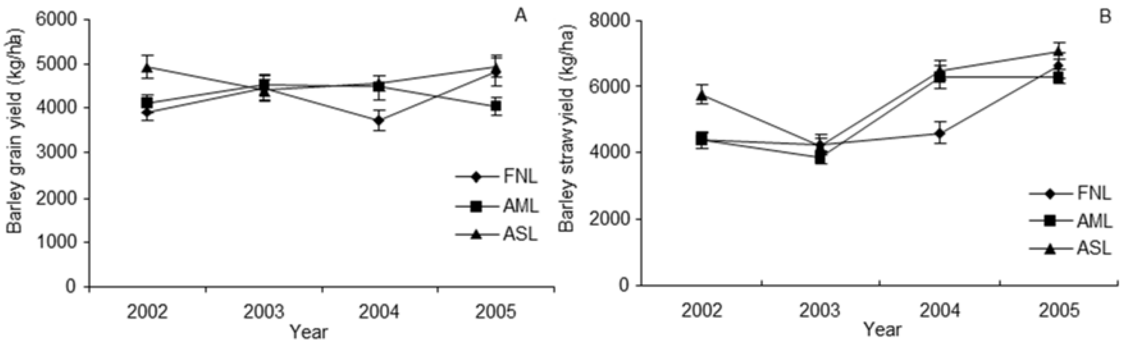

FIG.7. Grain yield (A) and straw dry matter (B) of barley in the 4–year experiment carried out in Yancheng, Jiangsu province, China from 2002 to 2005. Bars represent the Lsd (P<0.05).

Barley straw dry matter yield varied significantly over the five years (Fig. 7B). Generally straw dry matter yield was higher in ASL than in the other two treatments. In 2002 straw dry matter yield was highest in the ASL treatment. In 2003 and 2005 there were no differences between treatments. These changes in yield were possibly related to soil nutrient supply in the different years.

3.4. WATER USE EFFICIENCY OF RICE AND BARLEY

Both estimates of average water use efficiency (WUE) of rice differed significantly between treatments (Table 10). When WUE was calculated using the total water input (grain yield / rainfall + irrigation and total biomass / rainfall + irrigation) it was about three times higher in ASL and AML compared to the FNL treatment. However, when WUE was calculated based only on irrigation inputs (grain yield / irrigation, and total biomass / irrigation), the values were much higher in ASL and AML than in the FNL treatment, especially for the total biomass.

TABLE 10. AVERAGE WATER USE EFFICIENCY (kg m^{-3}) OF RICE BASED ON GRAIN YIELD, TOTAL BIOMASS, AND EITHER TOTAL WATER INPUT OR IRRIGATION INPUT

Treatment	Grain yield / rainfall + irrigation	Total biomass / rainfall + irrigation	Grain yield / irrigation	Total biomass / irrigation
FNL	0.04 b	0.06 b	0.05 c	0.08 c
ASL	0.11 a	0.19 a	0.60 a	1.05 a
AML	0.10 a	0.16 a	0.49 b	0.77 b

Data within a column followed by the same letter are not significantly different, DMRT at $P < 0.05$

Average WUE in barley was calculated using the rainfall inputs (Fig. 8). There were no significant differences between treatments for any of the estimated values. This effect is most likely due to the large variation in barley grain and total biomass yields (Fig. 8).

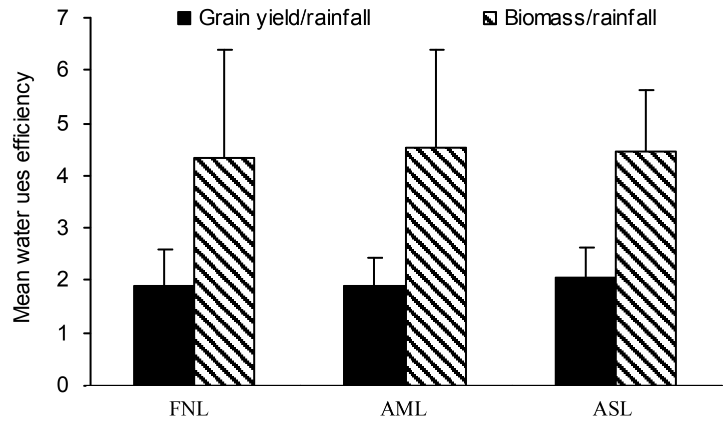

FIG. 8. Average water use efficiency of barley (kg m^{-3} × 10). Bars represent the Lsd (P<0.05).

3.5. NITROGEN USE EFFICIENCY

3.5.1. Difference method

The physiological N use efficiency (PNUE), agronomic N use efficiency (ANUE) and apparent recovery (AR) of fertilizer N for rice (Table 11) and barley (Table 12) varied with years and crops. The annual values of PNUE were significantly different in rice from 2002–05. PNUE values were significantly higher in 2003 and 2004 than in 2002 and 2005 (Table 11). This might be due to temperature variations between years. There were no significant differences in PNUE between FNL and ASL from 2002–04 but these two treatments had a higher PNUE than AML. In 2005 the AML treatment had the highest PNUE (Table 11). Mean PNUE values for four years were 59, 54 and 59 kg kg^{-1} for FNL, AML and ASL, respectively.

A similar trend was found in ANUE and AR. ANUE and PNUE were significantly lower in AML than in FNL and ASL. Mean ANUE values were in the order ASL>FNL>AML. PNUE and ANUE were lower in 2005 than in 2004 which may be the result of the lower temperatures in July and August in 2005 (Fig. 2). Mean AR values were 32, 30 and 35% for FNL, AML and ASL, respectively (Table 11).

TABLE 11. NITROGEN USE EFFICIENCY OF RICE CULTIVATED IN PADDY AND AEROBIC CONDITIONS WITH PLASTIC FILM AND STRAW MULCHING OVER FOUR SEASONS

Treatment	2002	2003	2004	2005	Mean
	PNUE (kg yield kg^{-1} N uptake)				
FNL	47.5 a	79.5 a	69.8a	38.0 b	58.7
AML	27.9 b	73.2 b	61.7b	51.0 a	53.5
ASL	43.2 a	81.6 a	64.2ab	46.7 a	58.9
	ANUE (kg yield kg^{-1} N applied)				
FNL	11.6 a	18.1 b	30.7a	15.9 b	20.1
AML	7.3 b	21.1 b	23.1b	12.9 c	17.2
ASL	11.8 a	25.2 a	26.2ab	20.4 a	20.9
	AR (%)				
FNL	24.7 b	22.4 b	39.2a	41.8 a	32.0
AML	27.5 b	31.6 a	37.0a	25.3 b	30.4
ASL	28.6 a	30.1 a	39.2a	43.6 a	35.4

Data within a column followed by the same letter are not significantly different, DMRT at $P < 0.05$

In barley, there were no significant differences between treatments in mean annual PNUE values (Table 12). Mean PNUE values were slightly higher in FNL than in AML and ASL. There were no significant differences in ANUE between treatments in 2003 or 2004. However, in 2005 and 2006 ANUE was significantly higher in AML and ASL than in FNL. Mean ANUE values for FNL, AML and ASL were 22, 25 and 25 kg kg^{-1}, respectively. A similar trend was found in AR values. When barley was cultivated in FNL, the apparent N recovery was lower than in AML and ASL. The highest mean value of AR was recorded in ASL.

TABLE 12. NITROGEN USE EFFICIENCY IN BARLEY GROWN AFTER RICE OVER FOUR SEASONS

Treatment	2003	2004	2005	2006	Mean
	PNUE (kg yield kg^{-1} N uptake)				
FNL	60.3 a	62.1 a	58.9 a	52.6 a	58.5
AML	57.9 a	60.7 a	54.8 a	56.4 a	57.5
ASL	54.3 a	59.3 a	54.3 a	53.8 a	55.4
	ANUE (kg yield kg^{-1} N applied)				
FNL	23.7 a	24.8 a	17.5 b	20.4 b	21.6
AML	23.9 a	25.9 a	25.1 a	24.6 a	25.0
ASL	22.9 a	25.4 a	25.7 a	24.9 a	24.7
	AR (%)				
FNL	39.3 a	39.3 a	29.7 b	38.8 b	36.8
AML	41.4 a	43.0 a	45.8 a	43.6 a	43.5
ASL	42.1 a	42.6 a	47.3 a	45.3 a	44.3

Data within a column followed by the same letter are not significantly different, DMRT at $P < 0.05$

3.5.2. Isotopic method

Fertilizer nitrogen use efficiency (FNUE, %) in rice grain and straw grown from 2002 to 2005 was determined with ^{15}N labelled urea and the results are presented in Table 13. On average, rice grain contained more ^{15}N than straw at harvest. The mean Ndff (kg ha^{-1}) of rice grain was highest for paddy rice cultivation. The mean Ndff (kg ha^{-1}) of straw was similar for the three treatments. FNUE values were not different between treatments in 2002 to 2003 whereas in 2004 and 2005 FNUE of FNL was significantly higher than that of AML and ASL. This was most likely due to variations in weather conditions [11]. Mean FNUE values for the four years were 29.5, 26.2 and 24.9% for FNL, AML and ASL, respectively.

TABLE 13. FERTILIZER N USE EFFICIENCY OF RICE CULTIVATED IN PADDY AND AEROBIC CONDITIONS WITH PLASTIC FILM AND STRAW MULCHING OVER FOUR SEASONS

Treatment	2002	2003	2004	2005	Mean
	Ndff (kg ha^{-1}) Grain				
FNL	38.6 a	39.5 a	48.1 a	30.5 a	39.2
AML	36.8 a	41.0 a	30.9 b	22.8 b	32.9
ASL	32.5 a	36.0 b	29.6 b	28.4 a	31.6
	Ndff (kg ha^{-1}) Straw				
FNL	15.3 a	11.6 a	12.1 a	17.0 a	14.0
AML	18.5 a	11.6 a	11.6 a	15.0 a	14.2
ASL	15.9 a	12.5 a	12.4 a	12.2 a	13.3
	FNUE (%)				
FNL	29.9 a	28.4 a	33.4 a	26.3 a	29.5
AML	30.7 a	29.3 a	23.6 b	21.0 b	26.2
ASL	26.9 a	26.9 a	23.3 b	22.5 b	24.9

Data within a column followed by the same letter are not significantly different, DMRT at P <0.05

The N derived from the fertilizer (Ndff) in the barley experiment varied between years (Table 14). Ndff (kg ha^{-1}) in barley grain was lower in FNL than in AML and ASL in all four years. Mean fertilizer N recovery determined by ^{15}N applied at a total rate of 120 kg N ha^{-1} was 20.6, 25.8, and 26.6% for FNL, AML, and ASL, respectively. Barley cultivated in ASL took up more N than in the other two treatments resulting in a higher FNUE in this treatment.

TABLE 14. FERTILIZER N USE EFFICIENCY IN BARLEY OVER FOUR SEASONS

Treatment	Ndff (kg ha^{-1})								FNUE (%)				
	Grain				Straw				Grain + straw				
	2003	2004	2005	2006	2003	2004	2005	2006	2003	2004	2005	2006	Mean
FNL	12.4 b	13.5 b	17.8 b	29.7 b	8.1 a	7.5 a	2.7 a	7.3 a	17.0 b	17.5 b	17.1 b	30.8 b	20.6
AML	15.7 a	14.4 b	26.7 a	35.4 a	10.8 a	9.8 a	3.8 a	7.0 a	22.1 a	20.2 ab	25.4 a	35.4 a	25.8
ASL	17.8 a	17.5 a	25.3 a	33.9 a	11.8 a	9.6 a	4.2 a	7.5 a	24.7 a	22.5 a	24.5 a	34.5 a	26.6

Data within a column followed by the same letter are not significantly different, DMRT at P <0.05

In all the four years the FNUE values determined by the ^{15}N isotopic method were lower than those determined by the difference method (Tables 11–14). It was also reported that higher values of AR were determined by the difference method compared to that determined by the isotopic method [12]. The higher NUE in ASL may be due to the immobilization of ^{15}N in the early stage by the residual of straw applied in the preceding rice season.

3.6. FERTILIZER N BALANCE

3.6.1. Total fertilizer N recovery in the soil–barley system

Barley fertilizer N recoveries ranged from 17–35% (Table 14). Fertilizer nitrogen recovery in the 0–40 cm soil layer was from 24–56% (Table 15). Thus, total fertilizer N recovery per cropping season in the soil–plant system was similar for the experimental treatments. There was a significant difference between treatments in both plant N and soil N recovery, but no significant difference in total N recovery between treatments.

Loss of fertilizer N estimated by mass balance ranged from 26–51% between treatments and years. This study has shown that rice cultivated in either paddy and aerobic soil with mulching had little effect on the fate of N in the following barley season.

TABLE 15. TOTAL FERTILIZER N RECOVERIES (%) IN SOIL (0–40 cm) AND SOIL + BARLEY OVER FOUR SEASONS

Treatment	Soil				Soil + barley			
	2003	2004	2005	2006	2003	2004	2005	2006
FNL	43.7	55.6	32.0	37.4	60.7	73.1	49.1	68.2
AML	44.9	53.7	24.1	32.9	67.0	73.9	49.5	68.3
ASL	42.1	49.2	31.3	35.3	66.8	71.7	55.8	69.8

3.6.2. Total fertilizer N recovery in the soil–rice system

Rice N recovery ranged from 21–33% (Table 13). N recovery in the 0–40 cm soil layer was 18–37% (Table 16), and unaccounted-for N estimated by mass balance was 36 to 61%. This indicates that more nitrogen was lost during the rice season than in the barley season. Fertilizer nitrogen losses were higher in AML than those in FNL and ASL.

TABLE 16. TOTAL FERTILIZER N RECOVERIES (%) IN SOIL (0–40 cm) AND SOIL + RICE OVER THREE SEASONS

Treatment	Soil			Soil + rice		
	2003	2004	2005	2003	2004	2005
FNL	30.8	30.8	22.9	59.2	64.2	49.2
AML	24.8	31.4	18.3	54.1	55.0	39.3
ASL	36.8	33.5	24.1	63.7	56.8	46.6

3.7. RESIDUAL FERTILIZER N RECOVERY

The uptake of residual fertilizer N by the subsequent crop is shown in Tables 17 and 18. From 0.5–2.4% of the N applied to the first rice crop was taken up by the following barley crop, and from 1.3–2.6% of the N applied to the preceding rice crop was taken up by the post rice crop. Past investigations on the residual effect of ammonium sulphate applied to rice on a bleached paddy soil from Jiangsu Province found that the recovery of residual N by the following rice crop was 20% of the fertilizer N remaining in the 0–20 cm soil layer [13]. These data are much higher than those obtained in the present study. The residual effect differences on the bleached paddy soil used in the present experiment could be due to the availability of "newly" fixed ammonium N being much higher than that of biologically immobilized N.

TABLE 17. UPTAKE OF RESIDUAL ^{15}N BY THE SUBSEQUENT BARLEY CROP OVER THREE SEASONS

Treatment	Ndff (kg ha^{-1})						NUE (%)			
	Grain			Straw			Grain + straw			
	2004	2005	2006	2004	2005	2006	2004	2005	2006	Mean
FNL	1.4 a	2.4 a	3.0 a	0.4 a	0.4 a	0.9 a	0.8 a	1.5 a	2.2 a	1.5
AML	1.0 a	3.2 a	2.9 a	0.5 a	0.5 a	0.6 a	0.5 a	2.1 a	2.0 a	1.5
ASL	1.4 a	2.7 a	3.7 a	0.5 a	0.6 a	0.6 a	0.8 a	1.8 a	2.4 a	1.7

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$

TABLE 18. UPTAKE OF RESIDUAL ^{15}N BY THE SUBSEQUENT RICE CROP OVER THREE SEASONS

Treatment	Ndff (kg ha^{-1})						NUE (%)			
	Grain			Straw			Grain + straw			
	2004	2005	2006	2004	2005	2006	2004	2005	2006	Mean
FNL	1.8 a	1.6 a	2.0 a	0.7 a	0.9 a	1.2 a	2.1 a	2.1 a	2.6 a	2.3
AML	1.4 a	2.0 a	1.0 a	0.7 a	0.9 a	0.6 a	1.7 a	2.4 a	1.3 a	1.8
ASL	1.4 a	1.9 a	1.4 a	0.5 a	0.7 a	0.7 a	1.6 a	2.2 a	1.7 a	1.8

Data within a column followed by the same letter are not significantly different, DMRT at $P<0.05$

4. CONCLUSIONS

Field experiments were carried out during the period 2002–06 to evaluate the effects of aerobic (unsaturated) and waterlogged cultivation on crop yield, NUE and WUE of a rice–barley production system at Yancheng Agricultural Institute, Nanjing, Jiangsu province, China.

Average grain yields of rice were higher in FNL and ASL than in AML over the five years of this experiment. However, there were no significant differences in rice yield between FNL and ASL. The average grain yield of barley was higher when it was cultivated following aerobically grown rice. The highest grain yield in the barley–rice rotation system was produced in the ASL treatment.

WUE in rice was about three times higher in ASL and AML than in FNL on the basis of total water input. However, the WUE was much higher in ASL and AML than in FNL when calculated by irrigation only input. There were no significant differences in WUE in barley between treatments.

The mean apparent N recoveries (AR) of rice were 32.0, 30.4 and 35.4% for FNL, AML and ASL, respectively. The mean AR values in barley were 36.8, 43.5 and 44.3% for FNL, AML and ASL, respectively.

The mean values of fertilizer N use efficiency (NUE) by rice were 29.5, 26.2 and 24.9% for FNL, AML and ASL, respectively. For barley, NUE was 20.6, 25.8 and 26.6% in FNL, AML and ASL, respectively. The following barley recovered from 0.5–2.4% of the ^{15}N fertilizer applied to the previous rice crop. From the results of this study it may be concluded that rice cultivated in aerobic soil with straw mulching could be used instead of paddy rice in a rice / barley rotation system in the northern part of Jiangsu Province.

ACKNOWLEDGEMENTS

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FERTILIZER NITROGEN MANAGEMENT FOR RICE GROWN ON PERMANENT RAISED BEDS IN SOUTH-EASTERN AUSTRALIA

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Abstract

Permanent beds have been proposed to increase the flexibility and profitability of rice–based cropping systems in South-eastern Australia. Growing furrow irrigated rice on beds introduces significant changes to the hydrology and aeration of the soil–plant system in comparison with continuously flooded rice culture, which may have a significant impact on the movement and transformations of fertilizer N in the soil and N use efficiency by the crop. Field experiments were, therefore, conducted to determine the most efficient but practical fertilizer N application methods for rice cultivated on beds. In 2003/04 and 2004/05, rice was grown on wide beds (1.84 m between bed centres) on a heavy clay soil in South-eastern Australia. Various splits of broadcast urea (150 kg N ha^{-1}) were compared, ranging from a single application at the 3–5 leaf stage (3L) to 2–3 splits at the 3L, mid tillering (MT), panicle initiation (PI) and heading (H) stages. Seasonal conditions were unusually cold in both years around the time of early pollen microspore, resulting in 2–3 times more sterility than in favourable years for rice. Yields of the fertilised treatments (6–7 t ha^{-1}) though superior to those of the N unfertilised treatment were considerably lower than the industrial average over the past few years in the region. Higher grain yield and harvest index (HI) were obtained with split applications up to PI compared with a single 3L application, with some significant differences. Plant recovery of applied ^{15}N in these split treatments was also significantly higher than with the single 3L application, while recovery in the soil and roots (0–70 cm) was not affected by application method. The majority of the fertilizer N recovered in the soil + roots was located in the 0–10 cm layer. Recovery in the plants was higher in the first year (single 3L, 28%; 3L + PI split, 40%) than in the second year (single 3L, 18%; 3L + MT + PI split, 35%, 3L + PI split, 34%). However recovery in the soil was higher in the second year (36–42%). Thus the total amount of unaccounted N ("N loss") was similar in both years – 46% for the single 3L application, compared with 24–30% in the split applications. Plant and soil recovery were not affected by position across the beds for single or split N applications, suggesting uniform distribution of the broadcast fertilizer N across the beds despite furrow irrigation. The results suggest that fertilizer N use efficiency can be improved with 2–3 split applications between the 3L and PI stages for rice grown on beds in this environment. Further research with an integrated approach to soil, crop, fertilizer and water management is needed to improve the sustainability of this cropping system in the region.

1. INTRODUCTION

Rice fields consume 50–70% of the water used in the irrigation areas in the semiarid, temperate climate of south-eastern Australia. In addition to the high water requirement to meet evapotranspiration demand, deep percolation from rice fields is a significant contributor to rising water tables and salinization [1]. The increasing price and declining availability of irrigation water, as a result of environmental and national competition policies [2], have prompted the search of more efficient water use in rice production systems [3]. It was proposed that growing rice on raised beds under furrow irrigation was an alternative to continuously flooded rice on "flat" layouts in the irrigation areas of South-eastern Australia

[4]. Bed farming is a system where soil is excavated to form furrows and is deposited beside them to form a raised cropping zone. The furrows act as irrigation channels, drains and traffic lanes, whilst crops are grown on the ridges. This permanent raised beds system has wide acceptance because it offers several potential advantages.

In South-eastern Australia, reductions in rice water use of 10–15% were found when rice was grown on raised beds (2 m between bed centres) with saturated soil, but yields were reduced by a similar amount [4]. In one of these studies N appeared to be yield limiting on the beds. A 6% reduction in input water use (irrigation plus rain) of furrow irrigated rice on beds over the traditional flat flooded layout was possible, but yields were also reduced by about 25% from 12.7 to 9.4 t ha^{-1}[5]. As the furrows had water in them for much of the time, the crop on beds took longer to mature, resulting in only a small water saving. The main reason for lower yield on the beds appeared to be due to the wide gap spacing (60 cm) between outside rows on adjacent beds.

N is usually the most limiting nutrient affecting rice yields. Nitrogen supply, transformations and uptake are well understood in conventional flooded rice culture on the flat layout, but there are few reports of N uptake, transformations and losses for furrow irrigated rice on raised beds. N losses from N fertilizer applied to rice on beds could potentially be much higher than in conventional systems due to alternating aerobic / anaerobic conditions over time and space with intermittent furrow irrigation. It has been hypothesised that increased loss of N due to nitrification / denitrification would occur when rice was grown on raised beds under fluctuating moisture regimes. However, results from field experiments in the USA indicated that the optimum N rate did not differ between furrow irrigated and flooded rice.

N fertilizer efficiency and grain yield are highest when N is applied prior to permanent flooding in conventionally grown rice crops in South-eastern Australia [6, 7]. The following N fertilization regimes were investigated for an intermittently (weekly) irrigated rice crop: i) all N applied in a single application at the three leaf stage (3L), the time of permanent flooding of conventionally cultivated dry seeded rice, ii) half of the N applied at 3L and half at panicle initiation (PI), and iii) one third of the N applied at 3L, one third at PI and one third between PI and anthesis [8]. Rice yields were reduced in all treatments, but the triple split application produced the highest grain yield. On a soil with high nitrification rates, it was found that 80% of fertilizer N was lost when it was applied to dry seeded rice at sowing followed by 3 flush irrigations [9]. N loss appeared to be associated with rapid rates of nitrification of ammonium when the soil was moist, followed by denitrification of nitrate once the soil became waterlogged [7].

In subtropical Queensland, wet and dry season rice was grown as follows [10]: i) permanent flood, ii) intermittent irrigation on the flat, or iii) with saturated soil culture on beds (SSC – water continuously ponded in the furrows). The second treatment had lower yields than the SSC and flooded treatments, which were not significantly different from each other. A study was also conducted in eastern Indonesia to investigate time of fertilizer N application for rice growing on raised beds were 0, 40 and 80 kg N ha^{-1} was broadcast as urea either all at sowing, half at sowing and half at PI, or all at PI. Grain yield was not affected by N treatment, but DM and grain number were significantly higher with the higher N rate, and panicle number was higher in the PI application [11].

The objective of the work reported here was to evaluate fertilizer N management practices of rice grown on permanent raised beds in south-eastern Australia over two years. The ^{15}N isotopic technique was used to determine fertilizer N recovery in the crop and soil and estimate the losses of fertilizer N applied to the bed / furrow system with a view to improving fertilizer N application efficiency in raised beds.

2. MATERIALS AND METHODS

In the first year (2003–04 season) an experiment was conducted to compare urea N application in a single application at the 3 leaf stage (single 3L) with a two equal (50: 50) split at the 3 leaf stage and at panicle initiation (3L + PI). In the second year (2004–05 season) the number of treatments was increased to include several two and three way splits of urea applied at selected rice growth stages. Detailed monitoring of the crop response to N management, soil mineral N status and ^{15}N recovery in the crop and soil was made.

2.1. EXPERIMENTAL SITE

The experiments were conducted at the Murrumbidgee Shire Community Experimental Demonstration Farm (34°44'S, 145°56'E), in the Coleambally Irrigation Area of South-eastern Australia. The soil is an association of Wilbriggie clay loam and Yooroobla clay [12], a transitional red brown earth and self-mulching clay, respectively. The soil had an apparent electrical conductivity (ECa – as determined using electromagnetic induction – EM31 – survey) range of 125–185 mS m^{-1}, and exchangeable sodium percentages (ESP) of 5–9% (0–60 cm) and 11–14% (60–150 cm), and thus it was classified as suitable for rice growing based on the rice soil suitability criteria [13].

The site was set up for evaluation of permanent bed rice–based cropping systems in mid-2002. Rice cv. Amaroo was grown from October 2002–April 2003. The plots received 27 kg N ha^{-1} (as di-ammonium phosphate) sown with the seed. The bays were split into six zones from east to west, each approximately 25 m long, and different N rate treatments were applied to each zone. The experiments reported here were conducted in zones 1 and 6, towards the ends of the bays. After the rice was harvested the stubble was slashed, the loose straw was removed from the plots, and the remaining stubble was burnt. In the 2003–04 rice season the western zones of the bays were used to conduct Experiment 1 described below. The experimental area was located on the second, third and fourth beds in from the northern side of each bay. In the 2004–05 rice season the eastern ends of the bays were used for small plot agronomic studies, while the microplots were placed in the western end to avoid cross contamination with ^{15}N.

2.2. WEATHER CONDITIONS

Weather data were obtained using a standard automatic weather station located about 30 m from the NW corner of the experimental site. Short wave radiation, wet and dry bulb temperature, relative humidity and wind run were measured every minute and hourly means were logged using a Campbell ® 21x logger. Rainfall was measured using a 0.2 mm tipping bucket rain gauge. Potential evapotranspiration (ETo) was calculated using a locally calibrated Penman combination equation [14].

The 2003–04 seasons were particularly bad for rice because cold weather occurred at the early pollen microspore (EPM) stage. Between 15 January and 5 February 2004, the air temperatures fell below 10°C on four occasions, and the minimum temperatures averaged 13.7°C during this period. As the threshold for low temperature damage to the developing pollen cells during EPM is 18°C, considerable sterility was anticipated, especially because deep water (for buffering against low night temperatures) was not maintained between panicle initiation and heading.

The 2004–05 season was again particularly bad for rice due to cold weather during EPM – one of the worst seasons on record. The 10-day average minimum temperature between 1to10 February 2005 was 12.9°C, and on two successive nights (2–3 February 2005), overnight temperatures fell to around 9°C. EPM in 50% of the rice crop was estimated to have occurred in the first week of February, thus induced pollen sterility was anticipated as a result of cold incidence.

2.3. EXPERIMENT 1

2.3.1. Experimental design

Three fertilizer N treatments were arranged in a randomised block design with four replicates. Topdressing of urea (150 kg N ha^{-1}) in a single application at the 3 leaf stage (single 3L) was compared with a two "split" (50: 50) application (150 kg N ha^{-1}) at the 3–5 leaf stage and at panicle initiation (3L + PI). The urea was uniformly broadcast onto the dry soil surface across the bed / furrow systems, followed by irrigation to wash the urea into the soil. The treatments were applied to small plots 4.1 m long by three beds wide (1.84 m per bed), giving a plot area of 23 m^2. There was also a zero N treatment. Steel micro plots (1.1 × 1.84 m) were installed across the middle bed of each fertilised plot for ^{15}N studies.

2.3.2. Field and crop management

Rice (cv. Quest) was sown at 140 kg seed ha^{-1} on 21 October 2003 using a combined seeder with Barton® parallelogram disc assemblies, set on 22 cm row spacing (the sowing method was UPDB unpuddled direct seeded beds). Eight plant rows were sown per bed with the outside two rows located on the shoulder of the bed, resulting in a 60 cm gap between the outside rows on adjacent beds. Diammonium phosphate was sown with the seed at 150 kg ha^{-1} in all plots, providing 27 kg N and 30 kg P ha^{-1}.

The experimental field received a germinating 'flush' irrigation on 22 October 2003 after sowing, in which water was applied via the furrows until it was 1 cm over the top of the beds; the furrows were then drained completely, taking approximately 24–36 h to complete the irrigation. A further four 'flush' irrigations were applied on 29 October, 6 November, 13 November, and 20 November. Following the first N application on 29 November, irrigation water was added, initially via the furrows, until there was a depth of 12 cm of water. The beds remained covered with water for around 12 days as the water depth slowly declined until the furrows were about one third full. The purpose of the prolonged ponding was to assist chemical weed control.

Continuous furrow irrigation was then initiated, with enough water applied to just cover the beds, then the water depth was allowed to decline until the furrows were about one third full before re-irrigating. The rice was ponded with deep water two more times during the season. On 2 December water was ponded to 12 cm above the beds to assist chemical control of the weed dirty dora (*Cyperus difformis*). The beds remained ponded for eight days. The beds were also ponded to a depth of 5 cm at PI (6 January), following the N application at PI, and remained covered for seven days before receding into the furrows. The main purpose of the ponding was to promote downward movement of the urea into the soil. After this, continuous furrow irrigation was continued until drainage at physiological maturity (PM) (23 March). The furrow irrigations occurred at 6–7 day intervals.

Water applications were measured into individual bays using constant head RBC flumes [15] equipped with Odyssey 392® water level recorders. The drainage from each bay was measured with circular flumes [16] and Odyssey 392® water level recorders. Water use by individual N management treatments within each bay could not be measured, but was unlikely to have been significantly different given that there was free water present for most of the time. Weed and pest control treatments were applied during the growth season as per recommended local agronomic management.

2.3.3. Crop monitoring and sampling

Phenological development was monitored throughout crop growth. Visual estimates of the dates of panicle initiation (PI), early pollen microspore (EPM), anthesis and physiological maturity (PM) were recorded. PI was estimated by slicing longitudinally up the stem from its base and determining the presence of a developing panicle. EPM was visually estimated by measuring the panicle length and by panicle colour, with EPM being when the panicle was 100 mm long and pale green. Anthesis was determined when anthers had emerged from florets in approximately 50% of the panicles. PM was determined by regularly harvesting grain samples and observing when it had declined to 28% moisture.

Plant establishment was determined at the 1–2 leaf stage by counting the number of plants in 1 m of each row across the third bed. One count was conducted in each replicate. Above ground dry matter (DM) production was determined at PI, anthesis and PM in all treatments. At PI and anthesis rice plants were cut at ground level from two quadrats per plot, each 0.92 m^2 (0.5 m long by the full bed width of 1.84 m) in the second and fourth beds. At PM, DM production and grain yield were determined from an area of 1.84 m^2 (1 m long by the full bed/furrow width of 1.84 m) in the third bed. Rice plant samples at PI and anthesis were processed to determine leaf area, stem weight, leaf weight, tiller density, N concentration of plant parts, N uptake and total biomass.

At PI and anthesis, thirty tillers were randomly selected from the quadrat sample and leaves were detached from stems and passed through a Licor 2000® leaf area analyser. The stems and leaves from the thirty tillers were dried at 80°C until they reached a constant weight which was recorded. A tiller subsample (100 g fresh weight) was also taken from the quadrat sample, cut into 15 cm lengths and microwave dried for six minutes. The sample was then dried in an oven at 70°C for 48 h, weighed, ground and analysed for N concentration with a LECO® combustion elemental analyser. The remaining plants from the sample cuts were dried in a dehydrator for one week at 80°C until reaching a constant weight which was recorded.

At PM plots were sampled to determine plant biomass and grain yield. The samples were oven dried at 80°C until they reached a constant weight. The samples were then threshed using a stationary Hege® thresher and the grain was weighed. A 30-tiller sub-sample was obtained by taking three to four tillers from each plant row just outside of the quadrat harvest area. The tillers were immediately processed into panicles and stems / leaves and oven dried at 70°C for 48 h and, then weighed. The grain was hand threshed and floret sterility was determined by separating and counting fertile and sterile florets. Average grain weight was calculated by passing a weighed amount of grain through a seed counter. Sterile florets were weighed and then combined with the stem / leaf sample prior to grinding and analysis by LECO® combustion for N concentration. The grains were ground separately and also analysed for N by LECO® combustion.

2.3.4. Soil sampling and mineral nitrogen determination

The soil was sampled to a depth of 30 cm using coring tubes of 46 mm diameter, which provided intact soil cores. The soil cores were then dissected into 0–5, 5–10, 10–20 and 20–30 cm sections to determine extractable nitrate and ammonium concentrations in the soil layers. There were five sampling times as follows: (i) just before the first fertilizer N application on 17 November (day 0), (ii) midway between the first and second N fertilizer application (day 26), (iii) PI just before the second fertilizer N application (day 41), (iv) anthesis, just after a furrow irrigation (day 79), and (v) PM, just after the bays were drained (day 129).

The soil samples were taken in the middle of the 4th bed on the 1st and 2nd sampling dates and in the middle of the 3rd bed on the last three sampling dates. Samples were taken from all three treatments in each replicate. At each sampling date, four cores were taken from each plot. Two cores were taken from within each plant row and two cores were taken from between the plant rows (both sides of the sampled row), and respective layers were bulked together. The soil samples were refrigerated immediately and processed within three days. A 40.0 g field moist soil subsample was extracted in 200 ml of 2M KCl. The extracts were analysed for NO_3^--N and NH_4^+-N using an Alpkem® analyser (APHA and AWWA 1992). At the same time as subsampling for extraction, 100 g subsamples were taken for determining gravimetric soil water content by oven drying at 103°C for 3 days and re-weighing.

Soil bulk density was also determined at PM in 0–5, 5–10, 10–20 and 20–30 cm increments using 5 cm and 10 cm high metallic rings with an internal diameter of 73 mm. The middle of the bed was sampled at PM in the zero N plots. The bulk densities and concentration of NO_3^--N and NH_4^+-N were used to calculate the amount of inorganic N in the soil in kg N ha^{-1}.

2.3.5. ^{15}N isotopic experiment

Two application methods were compared using ^{15}N-labelled urea (5 atom % ^{15}N) at a rate of 150 kg N ha^{-1}: a single application at the 3 leaf stage (single 3L) was compared with a two "split" application of 150 kg N ha^{-1} applied in a 50: 50 split at the 3–5 leaf stage and at PI (3L + PI). Steel micro plots (1.1 × 1.84 m) were placed in the centre of the 3rd bed in each replicate of the split (3L + PI) and single 3L application treatments for ^{15}N studies. The micro plots were 30 cm high and were inserted to 12 cm below the soil surface just prior to the first N application. The micro plots extended across the full width of the bed to the centre of both furrows and were designed to fit the shape of the bed (Fig. 1). Holes (38 mm diameter) were drilled near the four corners, just above the soil surface of the bottom of the furrow. Rubber bungs were placed in the holes and used to seal the micro plots for one to two weeks after fertilizer application to ensure that no fertilizer N left or entered the micro plots. The bungs were removed at other periods to allow irrigation of the micro plots via the main plots.

Water management within the micro plots was the same as that imposed in the main plots. Immediately after ^{15}N application, water from the irrigation supply channel was gently poured from buckets or pumped into the top end of each furrow in each micro plot to simulate furrow irrigation. Weed and pest control treatments were the same within as outside of the micro plots, but the micro plots were also hand weeded. Detached weeds were left in the micro plot following the first N application so that no ^{15}N was removed.

Soil samples were taken from within and immediately adjacent to individual rows across the centre of the micro plots. The soil was sampled to 70 cm in 0–10, 10–20, 20–30 and 30–70 cm sections. A total of six cores (46 mm diameter) to a depth of 20 cm were taken from each row / inter row to the middle of the bed – two within each plant row and two from either side of the plant row, and respective layers were bulked. The two core holes in each plant row were then augured to 70 cm using a 50 mm diameter soil auger, and the 20–30 and 30–70 cm soil sections were collected. Soil samples were immediately weighed and then dried at 40°C until they reached a constant weight. They were reweighed, crushed in a jaw crusher, mixed and sub sampled. One sub-sample was oven-dried at 103°C for three days and reweighed to determine residual moisture, so that gravimetric water content and bulk density could be calculated. Another soil sub-sample was obtained and further ground to a particle size <250 µm for total N and atom % ^{15}N analysis.

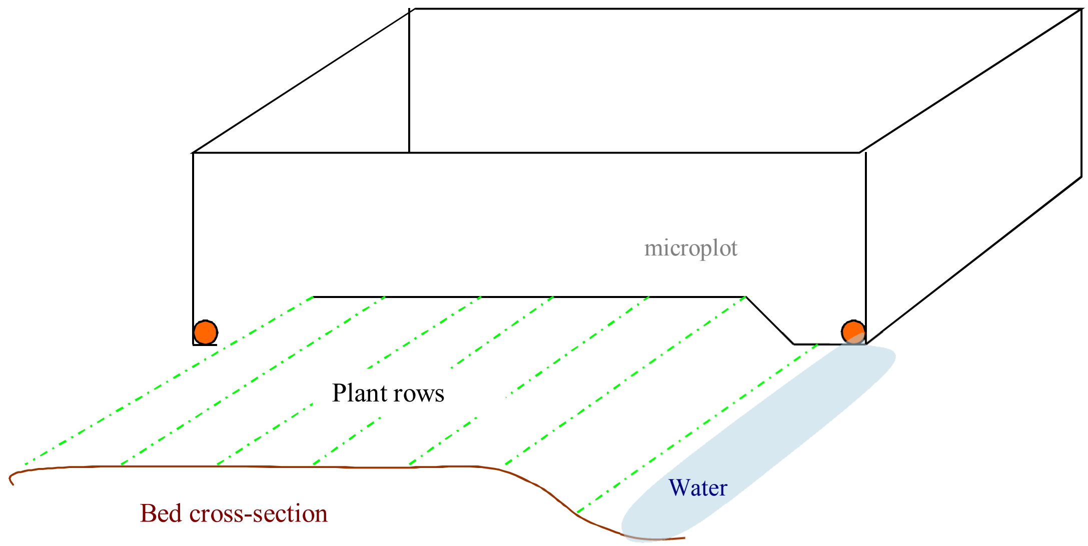

FIG. 1. Diagram of a micro plot with raised bed.

A single plant and soil sampling was made at PM in the micro plots. Sub samples were further ground in a ball mill so that it could pass through a 250 µm sieve. Total N and atom % ^{15}N were determined at the IAEA's Seibersdorf Laboratories using an Elemental Analyser coupled to an Isotope Ratio Mass Spectrometer. Samples of the ^{15}N-labelled urea used at each application time were also analysed for atom % ^{15}N. Plant samples and soil samples to 30 cm were also collected from the zero N plots for determination of background ^{15}N abundance.

2.3.6. Evaluation of nitrogen use efficiency

The amount of grain produced per unit of N uptake (physiological N use efficiency – NUE) and agronomic NUE (increase in grain yield per unit applied N) were determined for both methods of N application.

The apparent recovery of applied fertilizer N was calculated from the N uptake of the fertilised treatment minus the N uptake of the unfertilised treatment expressed as a percentage of the amount of applied N.

Using the ^{15}N data from plant and soil samples, N derived from the labelled fertilizer (Ndff) and N fertilizer recovery in plant and soil (0–70 cm) were determined. Fertilizer N losses from the soil–plant system were estimated by mass balance.

2.3.7. Statistical analysis

All data were analysed by analysis of variance using GenStat v. 6. Comparison of means was made by the Lsd test at $P<0.05$.

2.4. EXPERIMENT 2

2.4.1. Experimental design

A second experiment was conducted during the 2004/05 rice season at the same location. The experimental design was six N fertilization treatments arranged in a randomised block design with three replicates. Plots were three beds wide (5.5 m) by 7 m long, giving an effective plot area of 39 m^2. The six fertilizer N treatments were as follows:

- Single 3L – 150 kg N ha^{-1} in a single application at the 3 leaf stage (17 November 2004).
- 3L + PI split – 150 kg N ha^{-1} applied in an equal split at the 3–5 leaf stage and at PI (5 January 2005)
- 3L + MT split – 150 kg N ha^{-1} applied in an equal split at the 3–5 leaf stage and at mid tillering (15 December 2004)
- 3L + MT + PI split –150 kg N ha^{-1} applied in a three-way split with 50% applied at the 3–5 leaf stage and a further 25% applied at both mid-tillering (MT) and panicle initiation (PI)
- 3L + PI + H split – 150 kg N ha^{-1} applied in a three way split with 50% applied at the 3–5 leaf stage and a further 25% applied at both PI and heading (22 February 2005) and
- Zero N – no fertilizer N applied.

Urea was broadcast uniformly across the beds and furrows onto a dry soil surface, except for the application at heading when the beds / furrows were flooded to a depth of 6–8 cm above the beds at the time of application. Field operations and crop agronomic management were similar as described above for experiment 1.

2.4.2. ^{15}N isotopic experiment

Three split application methods were compared using ^{15}N-labelled urea (5 atom % ^{15}N) at a rate of 150 kg N ha^{-1} in a randomized block design with three replicates. The fertilizer treatments were as follows:

- Single 3L – Single application at the 3–5 leaf stage on 17 November 2004
- 3L + PI split – Two way split application with 50% at the 3–5 leaf stage and 50% at PI (5 January 2005)
- 3L + MT + PI split – Three way split with 50% applied at the 3–5 leaf stage, 25% at both MT and PI.

Steel micro plots were installed just prior to the first N application at the 3–5 leaf stage. The micro plots and methods of installation, N application and irrigation were as in 2003/04. Water management, weed and pest control within the micro plots were the same as in the main plots, but the micro plots were also hand weeded. Detached weeds were left in the micro plot following the first N application so that no ^{15}N was removed. Plant sampling in the micro plots was similar to that described above in the 2003/04 season. Soil samples were taken from each of the ten plant rows across the bed and corresponding soil layers were bulked into a single sample. One 30 cm deep soil core (46 mm diameter) was taken directly beneath each plant row across the bed and divided into 0–10, 10–20 and 20–30 cm sections. The holes in each plant row were then drilled using a 50 mm diameter soil auger, and 30–50 and 50–70 cm soil sections were collected. Soil samples were immediately oven dried at 70°C until constant weight.

2.4.3. Evaluation of N use efficiency and statistical analysis

Evaluation of N use efficiency and statistical analysis were made in a similar way to that described for experiment 1.

3. RESULTS AND DISCUSSION

3.1. EXPERIMENT 1

3.1.1. Crop performance in the small plots

Rice emergence occurred between 31 October and 3 November 2003. The zero N treatment reached PI one day before the split (3L + PI) treatment and two days before the single 3L treatment. EPM occurred on the same day in the split and single 3L treatments and one day earlier in the zero N treatment. A similar trend occurred at anthesis as PI, with the zero N treatment two days earlier to anthesis than the other two treatments. PM was delayed by 6 and 7 d in the single 3L and split N treatments, respectively, compared to the zero N treatment.

Plant density after emergence averaged 116 plants m^{-2}, well below the recommended target of 200–300 plants m^{-2}. The low establishment rate was probably due to seed placement being too deep in an attempt to sow seed into the shoulders of the beds. There was no significant difference in establishment in different rows on the bed (range 22–31 plants m^{-1} row).

At PI, dry matter (DM) was affected by treatment. DM at PI in zero N was significantly lower than the split and single 3L treatments, which were also significantly different from each other (Fig. 2). Similarly, N uptake, tiller density and leaf area index (LAI) were lower in the zero N than the split and single 3L treatments (data not presented). The single 3L treatment had significantly higher LAI and N uptake than the split treatment at PI. Total plant N concentration was significantly higher in the single 3L treatment than in the zero N treatment, and both were not significantly different from the split N treatment.

By the time of anthesis, DM production of the split N treatment had caught up to the single 3L treatment, while DM in the zero N treatment remained significantly lower than the fertilized treatments (Fig. 2). N uptake in the split treatment had increased by 130% since PI and was significantly higher than in both the single 3L and the zero N treatments, which were also significantly different from each other. LAI and tiller density of the split and single 3L treatments were similar at anthesis and significantly higher than in the zero N treatment. Tiller survival from PI to anthesis was lower in the single 3L treatment than the other two treatments. From PI to anthesis, tiller numbers declined by 6, 7 and 26% in the zero, split and single 3L treatments, respectively.

Biomass accumulation over time (Fig. 2) showed that the zero N treatment always had significantly lower DM than the other two treatments. The split treatment accumulated a larger amount of biomass between PI and anthesis than the single 3L treatment, but they did not differ in total DM accumulation after PI.

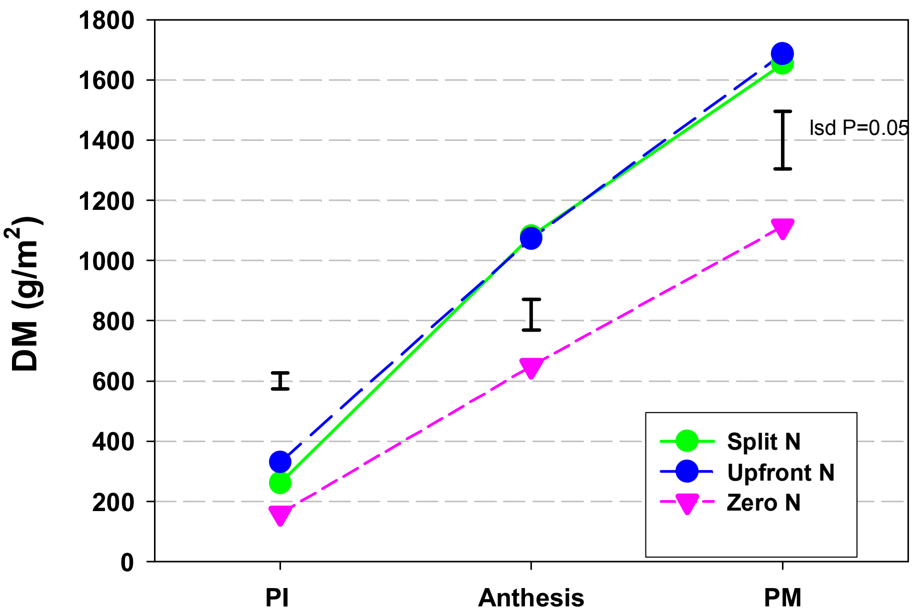

FIG. 2. Biomass accumulation over time in the small plots in 2003/04, Experiment 1 ("upfront" = urea applied in a single application at the 3 leaf stage (single 3L); "split" = 50: 50 split at the 3 leaf stage and panicle initiation (3L + PI).

At PM, there were no significant differences between the single 3L and split treatments for any parameter measured except for higher N uptake of the stems / leaves in the single 3L treatment. Both treatments had significantly higher total DM, grain yield, N uptake and panicle density than the zero N treatment.

Floret sterility was relatively high (23–29%) compared with values typical of seasons with no cold damage, but perhaps not as high as expected given the low temperatures during EPM. Percentage floret sterility was not affected by N treatment, in contrast with the findings of a significant interaction between N rate and water depth (protection against low air temperature) on floret sterility and yield [17], and in contrast with previous observations that the risk of sterility is greater where all the N fertilizer is applied early rather than as a split application. 1000–grain weight was also unaffected by N treatment, but the total numbers of florets panicle^{-1} and filled florets panicle^{-1} were significantly higher in the split N treatment than the zero N treatment.

3.1.2. Soil mineral nitrogen dynamics

Prior to the first N application, there was on average 75 kg N ha^{-1} extractable N in the top 30 cm, with slightly more as NH_4^+ than NO_3^-. By 26 days after the first N application, the amount of mineral N had declined to quite low levels, with no significant differences between the fertilised treatments (Table 1). The loss of NO_3^- was greater than that of NH_4^+. Between the time of the first N application and PI, inorganic N in the zero N treatment had declined by 68 kg N ha^{-1}, compared with total N in the plant tops at PI of 22 kg N ha^{-1}. It is likely that the entire NO_3^- present in the soil at the time of N application (~35 kg N ha^{-1}) was rapidly lost by denitrification as the beds remained ponded for eight days following N application. There were few significant differences between treatments in the amounts of NO_3^-, NH_4^+ or total mineral N present at any sampling time, and where the differences were significant they were too small to be of note. The lack of differences between treatments reflects that the first observations were made too late after N application – 26 days after the 1st N application and 38 days after the 2nd N application, by which time all of the applied N had been either immobilised (in the plants and soil) or lost. The data also indicate large amounts of soil mineralisation throughout the season. For example, the zero N plants took up 40 kg N ha^{-1} between PI and maturity, while mineral N levels in the top 30 cm were similar at PI and maturity (9 kg N ha^{-1}). The split treatment took up 60 kg N ha^{-1} over the same period, while mineral N levels declined by only 2 kg N ha^{-1} (from 11 to 9 kg N ha^{-1}).

TABLE 1. NITRATE, AMMONIUM AND TOTAL MINERAL N (kg N ha^{-1}) IN THE TOPSOIL (0–30 cm) AT EACH SAMPLING TIME IN THE SMALL PLOTS IN 2003–04, EXPERIMENT 1

Inorganic N	Days after N application at 3L (days after panicle initiation)				
	0	26	41 (0)	79 (38)	119 (78)
Nitrate	33.5	4.4	1.5	2.7	4.6
Ammonium	41.7	8.4	7.9	8.9	4.1
Total	75.2	12.8	9.4	11.6	8.7

There were no significant interactions between fertilizer N treatment and sampling time within depth for NO_3^-, NH_4^+ or total inorganic N (Fig.3 and Fig. 4), and no significant interactions between treatment and depth.

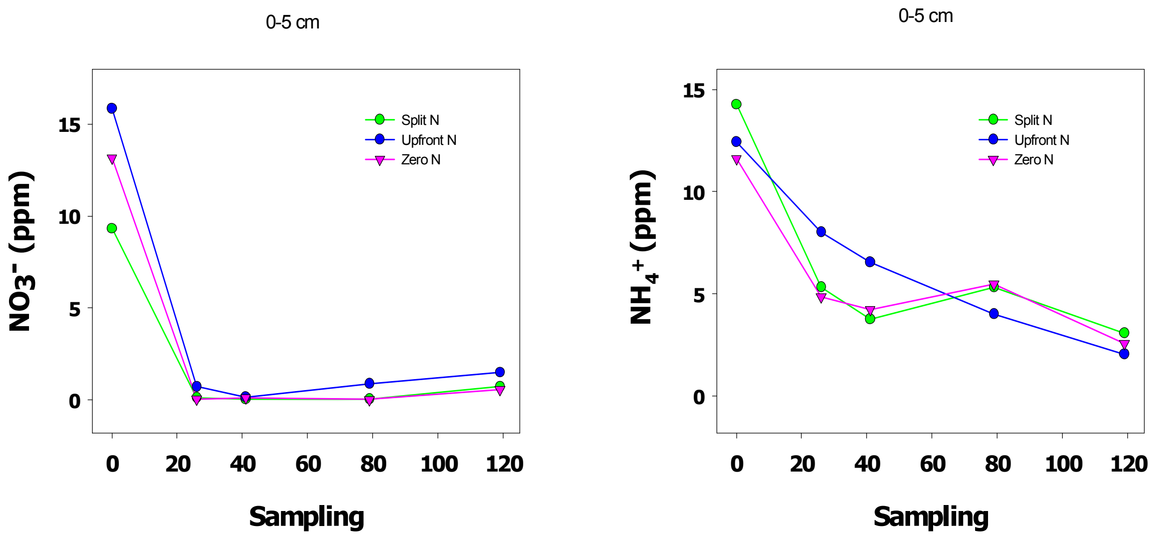

FIG. 3. Nitrate-N (left) and ammonium-N (right) concentrations (0–5cm) in the small plots at each sampling time (days after N application at 3L stage) in 2003/04, Experiment 1. ("upfront" = urea applied in a single application at the 3 leaf stage (single 3L); "split" = 50: 50 split at the 3 leaf stage and panicle initiation (3L + PI)

There was a significant effect of depth on NO_3^-, NH_4^+ and total inorganic N (Tables 2, 3 and 4). Prior to N application the concentrations of NO_3^- and NH_4^+ were highest in the upper layers and declined with depth. By 26 days after N application, NO_3^- concentration had declined to very low levels in all layers, and tended to by lowest in the 0–5 cm layer between

26 days after N application and maturity. NH_4^+ concentration had also declined greatly in all soil layers by 26 days after the first N application. However, NH_4^+ concentration was always much higher than NO_3^- concentration in all layers. NH_4^+ concentration generally decreased with depth throughout the season, and was always significantly higher at 0–5 cm than in deeper soil layers.

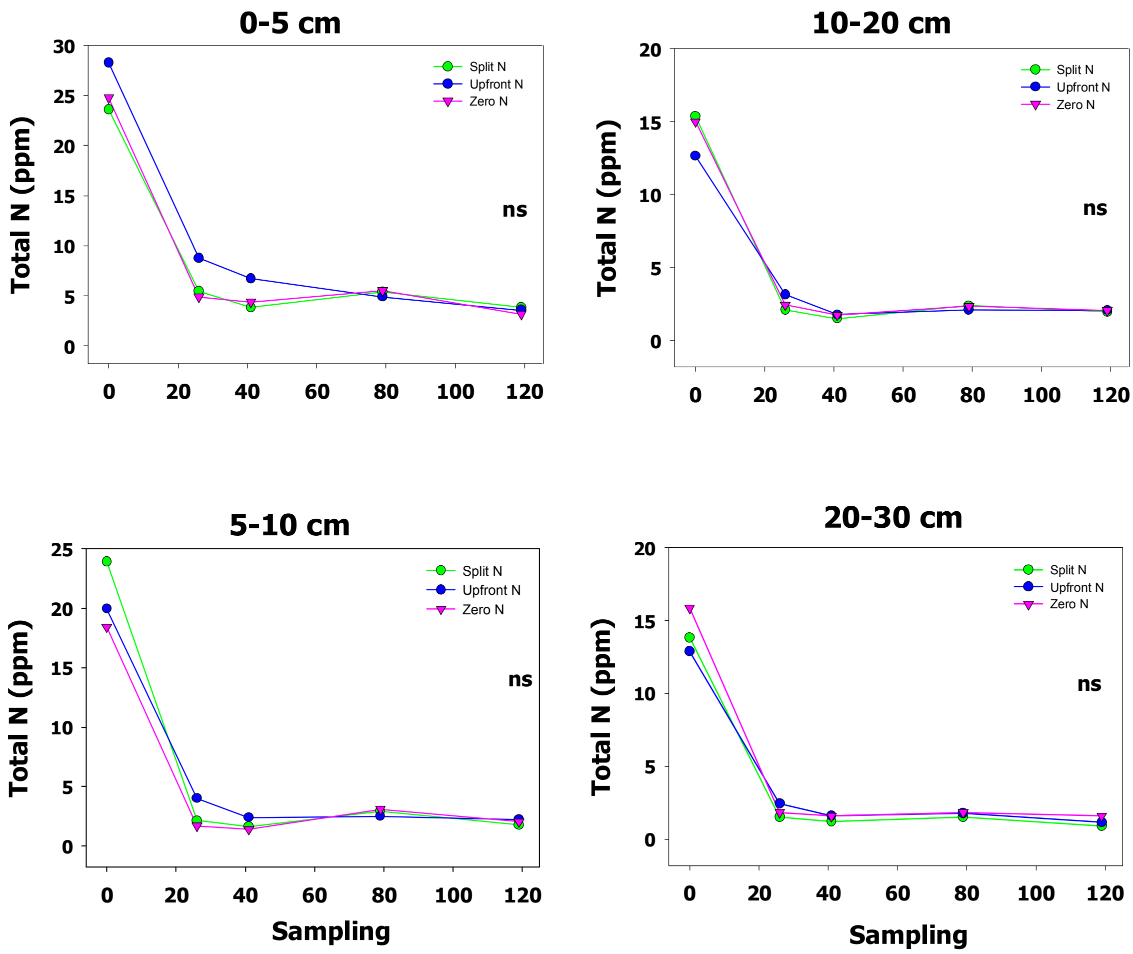

FIG. 4. Total mineral N in the small plots at each sampling time (days after N application at the 3L stage) in 2003/04, Experiment 1. ("upfront" = urea applied in a single application at the 3 leaf stage (single 3L); "split" = 50: 50 split at the 3 leaf stage and panicle initiation (3L + PI).

TABLE 2. NITRATE-N (mg kg^{-1} soil) IN SOIL LAYERS (MEANS OF N TREATMENTS) IN THE SMALL PLOTS IN 2003–04, EXPERIMENT 1

Depth (cm)	Days after first (3 leaf stage) N application (days after panicle initiation)				
	0	26	41 (0)	79 (38)	119 (78)
0–5	12.8	0.3	0.1	0.3	0.9
5–10	10.0	1.1	0.2	0.7	1.0
10–20	6.5	1.2	0.4	0.6	1.2
20–30	5.3	1.1	0.5	0.8	0.9
Lsd (P<0.05)	3.2	0.3	0.2	ns	ns

ns, not significant

TABLE 3. AMMONIUM-N (mg kg^{-1} soil) IN SOIL LAYERS (MEANS OF N TREATMENTS) IN THE SMALL PLOTS IN 2003–04, EXPERIMENT 1

Depth (cm)	Days after first (3 leaf stage) N application (days after panicle initiation)				
	0	26	41 (0)	79 (38)	119 (78)
0–5	12.8	6.1	4.9	4.9	2.6
5–10	10.7	1.5	1.6	2.1	1.0
10–20	7.8	1.4	1.3	1.7	0.8
20–30	8.9	0.8	1.0	1.0	0.4
Lsd (P<0.05)	2.8	1.4	0.3	1.2	0.6

TABLE 4. TOTAL MINERAL N (mg kg^{-1} soil) IN SOIL LAYERS (MEANS OF N TREATMENTS) IN THE SMALL PLOTS IN 2003–04, EXPERIMENT 1

Depth	Days after first (3 leaf stage) N application (days after panicle initiation)				
	0	26	41 (0)	79 (38)	119 (78)
0–5	25.5	6.4	5.0	5.3	3.5
5–10	20.8	2.6	1.8	2.8	2.0
10–20	14.3	2.6	1.7	2.3	2.1
20–30	14.2	1.9	1.5	1.7	1.2
Lsd (P<0.05)	4.4	1.4	0.6	1.3	0.7

3.1.3. Nitrogen use efficiency

Crop performance was also monitored in the micro plots (isotopic experiment). There was good agreement (within 10%) in crop performance in the micro plots and main plots for yield, yield components, N uptake and physiological NUE of respective treatments, with the exception that grain yield and N uptake in the split treatment in the micro plots was much higher (by about 20%) than in the small plots (data not reported here). This effect was associated with a higher N uptake in the shoots (stems / leaves) and total biomass of the plants of the split treatment growing in the micro plots.

Approximately 35% of the N in the rice plants was derived from the fertilizer, with no significant differences between the split and single 3L applications (Table 5). There was a small but consistent trend for the proportion of N derived from the fertilizer in the straw to be higher than that in the grain.

TABLE 5. PERCENTAGE OF N IN RICE PLANTS DERIVED FROM FERTILIZER (%NDFF) AND SOIL (%Ndfs) IN THE MICROPLOTS IN 2003–04, EXPERIMENT 1

Treatment	Grain		Straw	
	%Ndff	%Ndfs	%Ndff	%Ndfs
Split	39.2	60.8	43.5	56.5
Single 3L	32.5	67.5	37.1	62.9
Lsd (*P*<0.05)	ns	ns	ns	ns

ns, not significant

The data from the isotopic experiment are summarized in Table 6. ^{15}N fertilizer recovery for the rice plant was significantly higher in the split application treatment (40%) than that for the single 3L treatment (28%). ^{15}N fertilizer recovery in the soil (0–70 cm) was similar in both treatments (26–28%). The majority of the ^{15}N recovered in the soil was in the top 10 cm (20–21% of the applied N). Less than 1% of the applied N was recovered in weeds (0.8% in the split and 0.2 % in single 3L treatment). Total ^{15}N fertilizer recovery in plant and soil was significantly higher in the split (68%) compared with the single 3L (54%) application, largely due to higher recovery in the plant (Table 6). Almost one third (31% or 47 kg N ha^{-1}) of the applied N was unaccounted for in the split application, while almost half (46% or 70 kg N ha^{-1}) was unaccounted for in the single 3L application.

TABLE 6. FERTILIZER ^{15}N RECOVERY (% APPLIED ^{15}N FERTILIZER) IN THE PLANTS AND SOIL (0–70 CM) IN 2003–04, EXPERIMENT 1

Treatment	Plant	Soil	Total recovery
Split	40	28	68
Single 3L	28	26	54
Lsd (*P*<0.05)	6	ns	12

ns, not significant

Physiological N use efficiency – (NUE) was highest with zero N (75 kg grain kg^{-1} N uptake) and was similar (57–67 kg kg^{-1}) for both methods of N application (Table 7). Agronomic NUE was similar (11–14 kg kg^{-1}) for both methods of N application, as was apparent recovery of applied fertilizer N (25–33%). For the split application apparent fertilizer N recovery was less than ^{15}N fertilizer recovery, in contrast with most findings reported in the literature (Table 7).

TABLE 7. INDICES OF N USE EFFICIENCY (NUE) AND APPARENT FERTILIZER N RECOVERY IN THE SMALL PLOTS

Treatment	Physiological NUE (kg kg^{-1} N uptake)	Agronomic NUE (kg kg^{-1} N applied)	Apparent fertilizer N recovery (%)
Zero	75		
Split	67 (53)[a]	14	25
Single 3L	57 (51)	11	33

[a]Data in parentheses are from the microplots

Plant recovery data in this experiment were similar to the findings reported in the region for dry seeded rice on the flat with permanent flooding, but with different varieties and soil and climatic conditions. A plant ^{15}N recovery of 34% was found for urea applied at 70 and 140 kg N ha^{-1} while others have reported recoveries in the order of 32–40% with losses of around 25% [18, 19].

3.2. EXPERIMENT 2

3.2.1. Crop performance

Rice emergence occurred around the 1 November 2004. PI occurred between 12 and 18 January 2005 in all treatments. The zero N treatment reached all key growth stages (PI, EPM, anthesis, maturity) first, as in the previous year, while the two treatments that received N fertilizer applications at MT were always delayed relative to all other treatments. The single 3L, 3L + PI and 3L + PI + H split treatments reached PI around the same time, between the zero and 3L + MT split treatments.

EPM occurred between 26 January and the 2 February in all treatments. The zero and 3L + PI + H split treatments reached EPM first, followed by the single 3L and 3L + PI split treatments, followed by the two treatments that received N fertilizer at MT. Mid anthesis was reached on the 13 Feb 2005 in the zero N treatment. The 3L + PI + H and 3L + PI treatments were next to reach 50% anthesis (17 and 18 February, respectively), followed by the single 3L treatment (21 February 2005) then the two N fertilizer application treatments at MT (22 and 23 February 2005 for the 3L + MT + PI split and 3L + MT split treatments, respectively). PM was reached on the following dates in 2055: zero N (24 March), single 3L (28 March), 3L + PI and 3L + PI + H splits (3 April), 2 splits at MT (7 April). Good rice establishment on beds was achieved, with 242 plants m^{-2}. There was no difference in establishment between treatments, and plant density in rows across the bed was similar.

At mid tillering, DM production and LAI were significantly lower in the zero N treatment than in the fertilised treatments (Table 8). There was a trend for higher values with the single 3L treatment compared with split treatments, which had received 150 and 75 kg N ha^{-1} at the 3–5 leaf stage, respectively, but there were few significant differences. There was significantly higher N uptake and tissue N concentration in the single 3L treatment than in the split treatment, and both fertilised treatments had significantly higher N uptake and N concentration than the zero N treatment.

TABLE 8. CROP GROWTH AT MID TILLERING IN THE SMALL PLOTS IN 2004–05, EXPERIMENT 2

Treatment	DM ($g\ m^{-2}$)	N uptake ($kg\ ha^{-1}$)	Tillers (m^{-2})	LAI ($m^2\ m^{-2}$)	Tissue N ($g\ kg^{-1}$)
Zero	65	17.7	420	0.52	26.5
Single 3L	120	46.3	634	1.15	38.4
3L+MT split	103	35.7	520	0.91	34.1
Lsd (*P*<0.05)	26	9.0	ns	0.29	2.3

DM, dry matter; LAI, leaf area index; ns, not significant

At PI, DM, tiller density, N uptake and LAI in the zero N treatment were significantly lower than in all other treatments (Table 9). The 3L + MT split and 3L + MT + PI split treatments had significantly higher DM and N uptake than all other treatments, while 3L + MT split also had significantly higher tiller density and LAI than the single 3L, 3L + PI split and 3L + PI + H treatments.

TABLE 9. CROP GROWTH AT PANICLE INITIATION IN THE SMALL PLOTS IN 2004–05, EXPERIMENT 2

Treatment	DM ($g\ m^{-2}$)	N uptake ($kg\ ha^{-1}$)	Tillers (m^{-2})	LAI ($m^2\ m^{-2}$)	Tissue N ($g\ kg^{-1}$)
Zero	236	28.7	474	1.61	12.3
Single 3L	403	59.0	714	3.85	14.7
3L + MT split	521	101.7	871	4.39	19.6
3L + MT + PI split	480	101.3	785	4.18	21.3
3L + PI split	382	81.7	693	3.25	21.4
3L + PI + H split	406	80.3	689	2.96	19.7
Lsd (*P*<0.05)	76	17.6	135	0.86	3.8

DM, dry matter; LAI, leaf area index

By anthesis, all treatments had received 150 kg N ha^{-1} except the 3L + PI + H split which had only received 75% of this amount. At anthesis, the zero N treatment had significantly lower DM, tiller density, tissue N concentration, N uptake and LAI than all other treatments (Table 10). Both MT treatments had significantly higher DM and N uptake than all other treatments. Tiller density in the 3L + MT split was also significantly higher than in the single 3L treatment.

TABLE 10. CROP GROWTH AT ANTHESIS IN THE SMALL PLOTS IN 2004–05, EXPERIMENT 2

Treatment	DM ($g\ m^{-2}$)	N uptake ($kg\ ha^{-1}$)	Tillers (m^{-2})	LAI ($m^2\ m^{-2}$)	Tissue N ($g\ kg^{-1}$)
Zero	675	82.0	397	1.77	7.6
Single 3L	1060	156.0	568	4.35	8.2
3L + MT split	1281	251.3	655	5.45	9.4
3L + MT + PI split	1356	287.7	726	6.34	9.2
3L + PI split	1256	268.3	655	5.09	9.9
3L + PI + H split	1077	213.3	581	4.32	9.1
Lsd ($P<0.05$)	121	48.5	86	1.06	1.0

DM, dry matter; LAI, leaf area index

At PM total DM production, grain yield, N uptake and tiller density in the zero N treatment were again significantly lower than in all other treatments (Table 11). Total biomass of the zero N treatment was much lower than in the previous year, mainly due to lower grain yield and thus harvest index. The lower grain yield of the zero N treatment in the 2nd year compared with the 1st year was largely due to fewer florets panicle^{-1} and higher sterility. Dry matter was significantly higher in both treatments that received N at mid tillering than in the single 3L and 3L + PI + H split treatments. Tiller density in the two MT splits was also significantly higher than in the two PI splits. Grain yield was highest in the treatments that received N at mid tillering, but was not significantly different from other treatments, except the zero N treatment. Total N uptake was significantly higher in the two treatments that received mid tillering N, than in the zero N control, single 3L and 3L + PI + H treatments. The 3L + PI treatment had higher N uptake than the zero N treatment, but was not significantly different from all other treatments. There was no significant difference between treatments for HI.

TABLE 11. CROP GROWTH AND YIELD PARAMETERS AT PHYSIOLOGICAL MATURITY IN THE SMALL PLOTS IN 2004–05, EXPERIMENT 2

Treatment	DM ($g\ m^{-2}$)	Grain ($g\ m^{-2}$)	N uptake ($kg\ ha^{-1}$)	Panicles (m^{-2})
Zero	872	291	63.0	360
Single 3L	1537	563	113.7	596
3L + MT split	1848	686	151.3	661
3L + MT + PI split	1762	712	142.7	634
3L + PI split	1674	610	135.0	495
3L + PI + H split	1439	505	113.3	520
Lsd (P<0.05)	155	186	23.9	102

Floret sterility was higher than in normal warm years, ranging from 17% in the zero N treatment to 27% in the 3L + PI split treatment. These values were similar to those of the previous year, which also experienced low temperatures during EPM. There were no significant differences in floret sterility between treatments, as in the first year. The zero N, single 3L and 3L + MT split treatments had significantly higher 1000-grain weights than the treatments where some of the N was applied after MT i.e. the 3L + PI, 3L + PI + H and 3L + MT + PI split treatments (Table 12). The total number of florets panicle^{-1} was significantly higher where 50% of the N was applied at PI than in all other treatments, which had a similar number of florets panicle^{-1}. The 3L + PI split treatment had significantly more florets panicle^{-1} than all other treatments, which were not significantly different from each other. This resulted in more full florets panicle^{-1} in the 3L + PI split treatment, but this was not significantly different from the other treatments.

TABLE 12. GRAIN YIELD PARAMETERS IN THE SMALL PLOTS IN 2004–05, EXPERIMENT 2

Treatment	1000-grain weight (g)	Florets (panicle^{-1})	Filled florets (panicle^{-1})
Zero	27.7	51	42
Single 3L	27.7	53	43
3L + MT split	28.0	56	43
3L + MT + PI split	26.7	59	45
3L + PI split	26.3	76	56
3L + PI + H split	26.7	54	44
Lsd (P<0.05)	0.6	12	ns

ns, not significant

3.2.2. Soil mineral nitrogen dynamics

Prior to the first N application, there was an average of 105 kg N ha^{-1} mineral N in the top 30 cm, with slightly more NO_3^--N than NH_4^+-N. NH_4^+ concentration was greater than that of NO_3^- in the 0–5 cm layer. After fertilizer application, more NO_3^- and NH_4^+ were present in the single 3L treatment than the zero N treatment, and the amounts varied with depth (Fig. 5). By the time of the first sampling 36 h after urea application, the amount of urea detected in the soil was negligible.

The fertilised treatment consistently had a higher total mineral N concentration (Fig. 5). The amount and relative composition in terms of NH_4^+ and NO_3^- levels changed over time depending on irrigation water management. As inundation of the beds ceased NO_3^- concentration increased until the next inundating irrigation when NO_3^- levels fell again. This effect can be seen in Fig. 6 where total mineral N fell in the 0–5 and 5–10 cm depth intervals after the 2nd inundating irrigation while at the 10–20 cm depth interval the total mineral N concentration increased reflecting the increasing NO_3^- levels at this time.

3.2.3. Nitrogen use efficiency

Crop performance in the micro plots was monitored as reported above for experiment 1. In general, relative crop performance of the different treatments in the micro plots was similar to the corresponding treatments in the main plots. At physiological maturity, DM was significantly higher in both PI split treatments than in the single 3L treatment as in the small plots, and values in the micro plots were within 10% of values in the main plots (data not reported). Total N uptake in the micro plots was significantly higher in the split treatments, 3L + MT + PI split (138 kg N ha^{-1}) and 3L + PI split (124 kg N ha^{-1}) than in the single 3L treatment (104 kg N ha^{-1}), as in the small plots, and was within 10% of the values for the respective treatments in the small plots.

There were significant differences between the fertilizer treatments for percentage of N in the grain derived from fertilizer or soil. In the single 3L treatment, 75% of the N uptake came from the soil compared with about 60% in the 3L + PI and 3L + MT + PI split treatments (Table 13). On the average, N in the plant (grain + straw) derived from the fertilizer was about 40% in the split treatments compared to 27% in the 3L treatment.

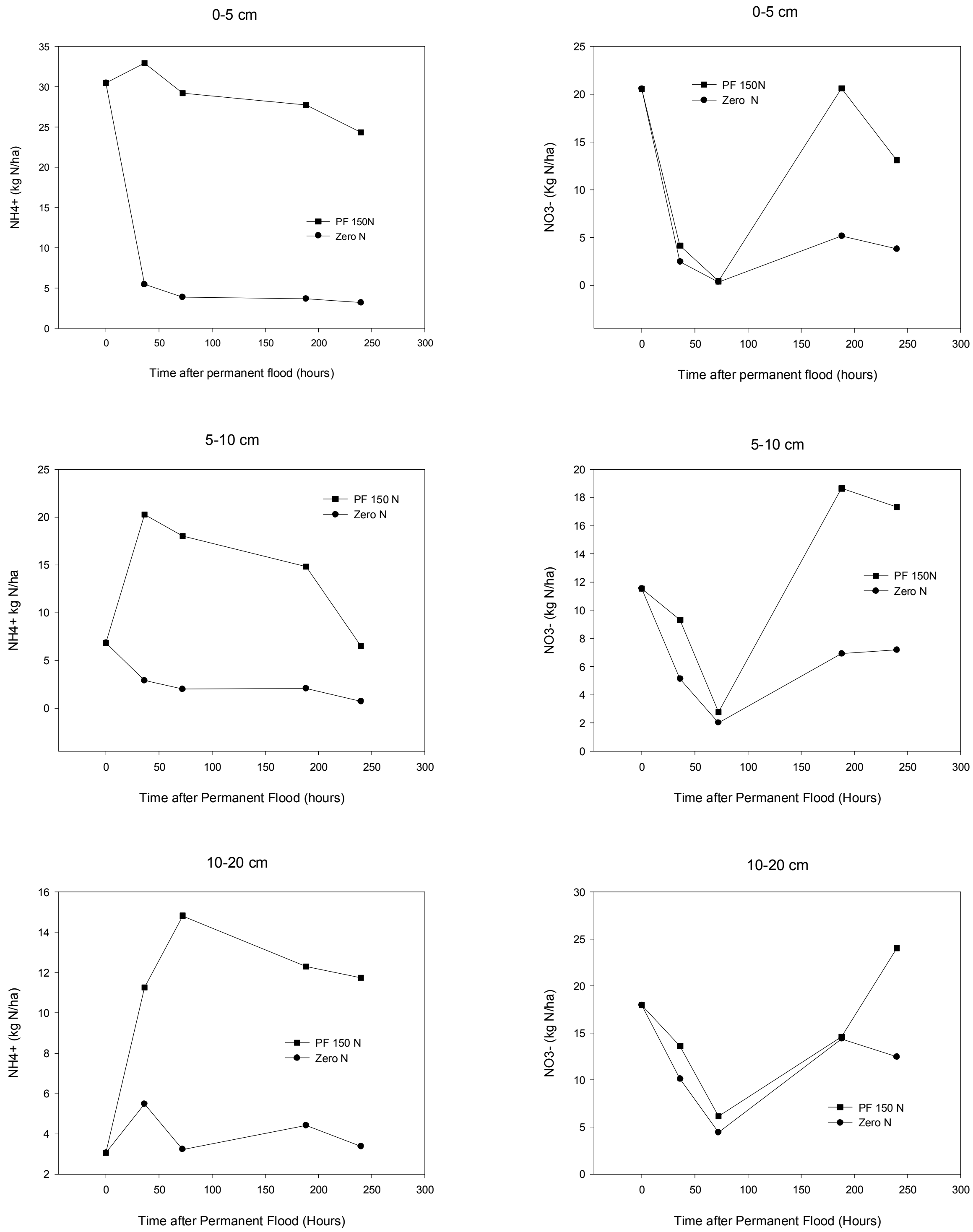

FIG. 5. Changes in exchangeable ammonium (left) and nitrate (right) with time (hours after urea application at the 3–5 leaf "PF" stage) in the small plots at each soil sampling depth in 2004–05, Experiment 2.

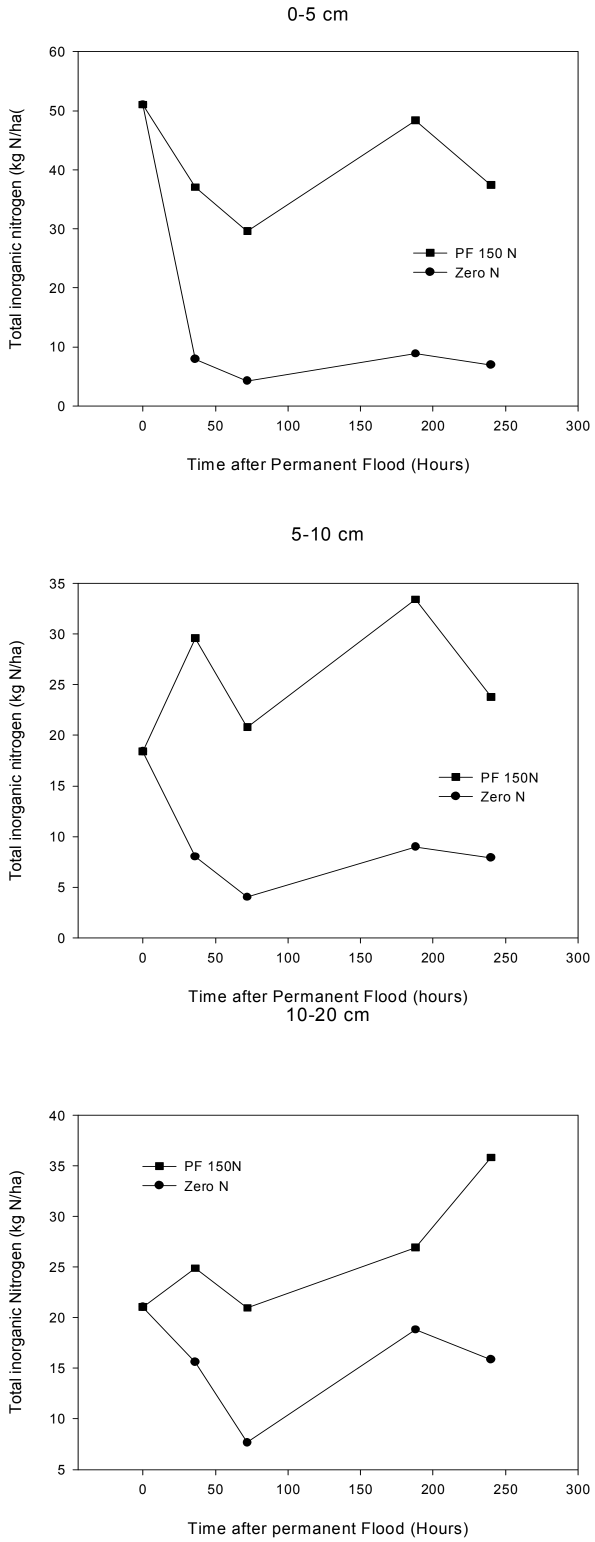

FIG. 6. Variations in total mineral N with time (hours after urea application at the 3 leaf "PF" stage) at each soil sampling depth in the small plots at each sampling time in 2004–05, Experiment 2.

TABLE 13. NITROGEN IN RICE PLANTS DERIVED FROM FERTILIZER (%Ndff) AND SOIL (%Ndfs) IN THE MICROPLOTS IN 2004–05, EXPERIMENT 2

Treatment	Grain		Straw		Grain + straw
	%Ndff	%Ndfs	%Ndff	%Ndfs	%Ndff
Single 3L	25.2	74.8	28.2	71.8	26.5
3L + MT + PI split	36.1	63.9	42.3	57.7	38.9
3L + PI split	40.8	59.2	42.6	57.4	41.6
Lsd (*P*<0.05)	3.3	3.3	3.8	3.8	3.0

The recovery data from the isotopic experiment are summarized in Table 14. ^{15}N fertilizer recovery for the rice plant was significantly higher in the split application treatments (34–35%) than that for the single 3L treatment (18%). ^{15}N fertilizer recovery in the soil (0–70 cm) was similar in all treatments (36–42%) but was higher than in the previous year (26–28%). The majority of the ^{15}N recovered in the soil was found in the top 10 cm (20–29% of the applied N). Around 4% of applied ^{15}N was recovered from the 10–20 cm soil layer, and fertilizer N at deeper soil layers (down to 70cm) accounted for between 1.6 and 2.4% of applied ^{15}N. Total ^{15}N fertilizer recovery in plant and soil was similar to that found in the 2003–04 season for both split applications and with significantly higher recovery in the split treatments (76% and 73%, respectively) than the single 3L application treatment (54%) (Table 14). The higher recovery in the split treatments was largely due to higher uptake and recovery in the plants, as in the previous year. Around one quarter (24% and 27%) of the applied fertilizer N was unaccounted for in the 3L + PI split and 3L + MT + PI split treatments respectively, while almost half (46%) was unaccounted for in the single 3L application treatment.

TABLE 14. FERTILIZER ^{15}N RECOVERY (% APPLIED ^{15}N FERTILIZER) IN THE PLANT AND SOIL IN 2004–05, EXPERIMENT 2

Treatment	Total plant	Soil (0–70 cm)	Total
Single 3L	18.2	36.0	54.1
3L + MT + PI split	35.1	37.9	73.1
3L + PI split	33.9	41.9	75.8
Lsd (*P*<0.05)	7.5	ns	13.5

ns, not significant

Physiological NUE was similar across treatments, and although similar in the small and micro plots (Table 15) was greater in the small plots. Apparent fertilizer N recovery was much higher than ^{15}N fertilizer recovery in all treatments.

TABLE 15. NITROGEN USE EFFICIENCY (NUE) INDICES AND APPARENT FERTILIZER N RECOVERY IN THE SMALL PLOTS

Treatment	Physiological NUE (kg kg^{-1} N uptake)	Agronomic NUE (kg kg^{-1} N applied)	Apparent fertilizer N recovery (%)
Zero	46		
Single 3L	50 (44)[a]	31	33.8
3L + MT + PI split	50 (43)	28	53.1
3L + PI split	45 (37)	21	48.0

[a]Data in parentheses are from the microplots

4. CONCLUSIONS

Field experiments were carried out to evaluate N management practices of rice grown on permanent raised beds in South-eastern Australia over two years (2003–04 and 2004–05). The ^{15}N isotopic technique was used to determine fertilizer N recovery in the crop and soil and to gain insight into the transformations and losses of fertilizer N applied to the bed / furrow system with a view to improving fertilizer N application efficiency in raised beds.

Yields of the fertilised treatments (6–7 t ha^{-1}) were superior to the control (no application of fertilizer N) treatment but considerably lower than the industrial average obtained in the region over the past few years. The results of this study were generally similar across the two seasons but rice growth and yield in both seasons were markedly affected by the occurrence of abnormally low temperatures during the early pollen microspore stage and subsequent effects on floret fertility levels.

Soil mineral N dynamics (forms and concentrations) were highly variable with time after fertilizer N application and soil sampling depth. Overall, it was largely dependent upon irrigation water management.

The ^{15}N studies showed a significantly higher fertilizer N recovery by rice with split applications compared to the single application time while recovery in the soil and roots (0–70 cm) was not affected by application method. The majority of the fertilizer N recovered in the soil / roots was located in the 0–10 cm layer. Recovery in the plants was higher in the first year (single 3L, 28%; 3L + PI split, 40%) than in the second year (single 3L, 18%; 3L + MT + PI split, 35%; 3L + PI split, 34%), but recovery in the soil was higher in the second year (36–42%). Thus the total amount of unaccounted N (“N loss”) was similar in both years – about half (46%) for the single 3L application, compared with one fourth to one third (24–30%) for the split applications. No significant differences were found between the studied split applications, and thus 150 kg N ha^{-1} in two equal split application (3L + PI) may be recommended for rice grown in beds in this environment.

Further research with an integrated approach to soil, crop, fertilizer and water management is needed to improve the sustainability of this cropping system in the region.

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INTERACTIONS BETWEEN SILICON AND PHOSPHORUS IN FLOODED AND NONFLOODED SOILS DETERMINED BY ^{33}P AND ^{32}P.

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Abstract

A series of pot and laboratory experiments were conducted to examine the effect of additions of silica minerals on fertilizer P reactions in soils and rice growth. The use of ^{33}P and ^{32}P isotopes allowed the separation of native soil P and fertilizer P sources and identified that the added silica materials alter fertilizer P / soil reactions by modifying adsorption / desorption processes. In one experiment addition of acidulated rock silica (ARS) with fertilizer P increased rice tops growth more than fivefold and increased the fertilizer P recovered in the tops from 0.9–5.1%. In a second experiment the rice growth response was not as large but yield and fertilizer P uptake responses to P addition were recorded when silica sources (unacidulated and acidulated rock silicate and calcsilicate were applied. In a third experiment pre flooding of the soil resulted in an eight-fold reduction in the concentration of fertilizer P in the soil solution compared to the non-flooded soil. The addition of ARS increased the yield of rice tops and total and fertilizer P uptake in both flooding treatments, with the % of fertilizer P in the plant higher in the pre flooded (23.3%) compared to the unflooded (19.5%) soil. Two P adsorption studies showed that ARS adsorbs P, one third of which can be desorbed over 24 days, indicating that the increase in P use efficiency resulting from the addition of ARS is likely to be due to the fertilizer P being preferentially adsorbed and weakly held on the silicate material, which is released over time. The results indicate that addition of ARS with P fertilizer to a rice crop grown in a non-flooded soil or a non-flooded crop grown after a flooded crop, as in a rice–wheat rotation, can substantially improve yields and P use efficiency. Further research is needed to confirm these results in field studies.

1. INTRODUCTION

Much research has been performed on the silicon (Si) requirements of rice and sugarcane and it has been generally concluded that silicon is essential for these two crops [1]. However, rice will grow and mature satisfactorily in hydroponic solution devoid of Si, and therefore Si does not meet the criterion of an essential nutrient. This leaves the question of an alternative role for Si in rice culture [2].

In rice–wheat systems, where the soil water regime changes from flooded to unflooded conditions and soil redox potential shifts from reduced (anaerobic) to oxidize (aerobic) conditions, phosphorus (P) dynamics in soils and its availability to plants also change rapidly. In early experiments conducted in Australia, it was found that poor pasture growth following flooded rice was caused by a lack of plant available P resulting from P adsorption onto active sites which had been exposed by the flooding conditions imposed in the rice crop [3].

In a series of field and glasshouse experiments conducted in Australia by English (pers. comm.) application of acidulated rock silicate (ARS) has resulted in small and variable yield increases when applied with P fertilizer.

This study was conducted to gain a better understanding of the influence of silica on soil P dynamics under flooded and non-flooded conditions in order to contribute to the sustainable production of the rice–wheat system in Asia. The specific objectives were: i) to determine the impact of additions of silica on the dynamics of fertilizer P in soil, and ii) to determine the impact of soil water status on the soil P and Si in a rice–wheat system.

2. MATERIALS AND METHODS

2.1. EXPERIMENT 1

In order to better understand interactions between Si and P and the impact of Si fertilisation on rice yield, an initial glasshouse experiment was conducted. Two P treatments namely plus P (+P, 35 kg P ha^{-1}) and minus P (–P) additions were imposed on a P deficient, acid sandy soil, collected from Queensland, Australia. In the –P treatment carrier free ^{32}P was added in order to be able to use reverse dilution to identify the source of soil P to the plant and for desorption studies. In the +P treatment $KH_2{}^{32}PO_4$ with a specific activity (SA) of 0.4 MBq mg^{-1} P was applied.

The Si treatments included minus Si (–Si) and plus Si (+Si) added as two Si sources. The silica sources were Acidulated Rock Silicate (ARS) at 100 kg ha^{-1} and a 50: 50 mixture of ARS and calcsilicate at 150 kg ha^{-1}. The applied rates were estimated to supply the same amount of available Si as determined by $CaCl_2$ extraction. Rice was grown as the test crop and plant Si and P concentrations and ^{32}P activities were determined.

2.2. EXPERIMENT 2

An acid, light textured soil from Elong Elong, NSW, which was responsive to P, was used in the main experiment. The soil was divided into forty four separate lots of 850 g and 300 g in plastic bags so that the treatments and basal nutrients could be applied to the top surface of the 850 g lot. Carrier free ^{32}P solution (2 ml) containing 3.7 MBq of ^{32}P was added to each 850 g lot. This solution was mixed throughout the soil and the bags were incubated in the glasshouse for 30 days to equilibrate the ^{32}P with the indigenous soil P. This allowed for the reverse dilution technique [4] to be used to determine P originating from native soil P pools. Because of the very low P status of the soil an application of 5 kg P ha^{-1} as $(NH_4)_2H^{32}PO_4$ was made to all the pots and an additional application of 15 kg P ha^{-1} as $(NH_4)_2H^{33}PO_4$ was added to the +P treatment. ^{33}P labelled fertilizer was used to be able to distinguish the P derived from the fertilizer from the native soil P.

In a first study (Experiment 2a), the effect of silica (–Si and +Si sources: Unacidulated and acidulated rock silicate and calcsilicate) and phosphorus (P and +P) on rice growth and P uptake were determined. Also P dynamic studies, i.e. changes in ^{32}P activity in the soil solution and P desorption were carried out.

In a second study (Experiment 2b), the effect of flooding (unflooded and pre flooding) and silica (–Si and +ARS) on rice growth and P uptake were investigated. Flooding was undertaken by placing the treated soil in a plastic bag in a pot, fully submerging it and maintaining 1cm of water over the soil surface for 30 days. The soil was then allowed to evaporate to dryness. At the end of the equilibration period the bags were opened and placed inside 15 cm plastic pots. The pots were tapped on a hard surface to firm the soil and the test fertilizer materials (application rates based on pot surface area) applied in a uniform layer. The materials applied in the experiments are shown in Table 1.

After addition of the treatments in a layer on top of the 850 g soil, soil solution samplers [5], were inserted in a vertical helical manner through the banded fertilizer material in each pot. The tubing used to connect the hollow fibre sample externally was sealed with a double ended needle and soil solution was collected after wetting the soil up to field capacity overnight (Fig. 1).

TABLE 1. DETAILS OF TREATMENTS USED IN EXPERIMENTS 2a AND 2b

Treatment	Source/s	Application rate (kg ha^{-1})	Comment
– / +P	$(NH_4)_2H^{32}PO_4$ and $(NH_4)_2H^{33}PO_4$	0.5 15	Applied in solution. All pots received 0.5 kg P ha^{-1} through reverse dilution labelling. The +P pots received 15 kg P ha^{-1} as labelled fertilizer in a band
Si sources	Unacidulated rock silicate (URS)	43	Si source application rates were based on the estimated Si release and additions adjusted to provide 7.2 kg ha^{-1} of mono silicic acid, in the band
	Acidulated rock silicate (ARS)	60	
	Unacidulated calcsilicate (UC)	36	
	Acidulated calcsilicate (AC)	45	
Flooding			The +P +ARS treatment was applied to 4 replicates of both pre flooded and unflooded soil

FIG. 1. Soil solution samplers placed in each pot.

2.2.1. Production of Si containing materials

The Si rock materials were obtained from naturally occurring deposits in Australia. They were pulverized to <106 microns. The acidulated materials were treated with sulphuric acid, water and lime.

2.2.2. Production of ^{33}P labelled fertilizer

The labelled P fertilizer was made by adding 370 MBq of carrier free ^{33}P to 4 g $(NH_4)_2HPO_4$ (938 mg P) in 500 mL to give a solution of di-ammonium phosphate (DAP) with a specific radioactivity (SR) of 0.395 MBq mg^{-1} P.

2.2.3. Plant establishment and growth conditions

When the fertilizer materials had been added to the pots the 300 g of soil which had been kept separate was used to cover the fertilizer layer and 4 day old rice seedlings (*Oryza sativa*) cv. Jarrah were transplanted, taking care not to disturb the fertilizer layer.

The pots were regularly watered to field capacity. Soil solution was extracted from the samplers into a vacutainer 1, 6 and 46 days after transplanting and ^{32}P and ^{33}P activities were determined. The plants were cut close to the soil surface 35 days after transplanting, and the tops were dried at 80^{o}C until constant weight, and then ground to pass a 2 mm sieve for chemical analysis.

After harvest of the tops the soil was removed from the pots inside the plastic bag and laid on a plastic tray. The soil solution sampler and visible roots were removed, the soil was thoroughly mixed and a subsample taken for chemical analysis.

2.2.4. Chemical analysis and radio assay

It was originally intended to label Si with ^{30}Si but in preliminary studies problems were encountered in the measurement of ^{28}Si, ^{29}Si and ^{30}Si isotopes in an ICP-MS with interference from N_2 with a mass of approximately 28. Because of this it will be necessary to move from an ICP-MS to an ICP Plasma Sector Field MS (ICP-SFMS) [6] to be able to measure ^{30}Si enrichment in the samples, but this has not been possible in this study.

Measurements of ^{32}P and ^{33}P activity were made in a 3 channel liquid scintillation counter (LSC) on 1 ml aliquots of soil solution and digests of plant tops. The scintillant was described by Till et al [7]. The counter windows were set at 0–100, 100–1700 and 0–1700 mV. Counts in each window were corrected for background, spill over and decay and all isotope data are expressed on a day zero basis.

Plant samples were digested using a microwave digestion process in concentrated nitric acid and hydrogen peroxide. Phosphorus and Si were determined using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICPAES) to avoid potential interference between Si and P which occurs with colorimetric assay.

2.3. EXPERIMENT 3 (P ADSORPTION AND DESORPTION STUDIES)

Two adsorption / desorption studies were undertaken. In the first study the sources were unoxidised rock silicate; rock silicate oxidized at high temperature and rock silicate oxidised at low temperature.

Either 50 or 100 μg P was added to 0.1 g of each Si source, corresponding with a loading of 500 or 1000 μg P g^{-1} Si source, respectively. Desorption was achieved by adding 20 mL of 0.01 M $CaCl_2$ to each tube and shaking for 1 hour prior to centrifugation and analysis for P in the supernatant using malachite green. The Si sources were allowed to dry completely between desorption cycles and the amount of P left in the entrained solution determined. Even at the highest P ‘desorbed’ this accounted for <2 μg P.

In the second study a range of acid concentrations were achieved by adding acid and lime to acidulate the rock silicate and adsorption was measured at a single point using the procedures described above.

The Specific Radioactivity Ratio (SRR), which is the ratio of the specific radioactivity of the P in the +P treatment to the specific radioactivity of P in the –P treatment [4] was used to calculate (1 – SRR) x 100 to estimate the percentage of P in the plant derived from the fertilizer. Recovery of P was calculated as:

$$\% \text{ recovery} = \frac{\text{Fertilizer P } (1 - \text{SRR}) \times \text{Total P in plant (mg pot}^{-1}) \times 100}{\text{P added (mg pot}^{-1})}$$

3. RESULTS

3.1. EXPERIMENT 1

There was a marked response in dry matter yield of rice tops to P fertilizer when applied in the presence of a Si source, with the greatest response in the 100 kg ha^{-1} ARS treatment (Table 2). Uptake of P in tops followed a similar trend. The soil pH decreased when P fertilizer was added as di-ammonium phosphate in the absence of Si, remained constant in the mixed Si source treatment and increased when ARS was applied with the P fertilizer (Table 2).

TABLE 2. DRY MATTER YIELD AND P UPTAKE BY RICE TOPS IN EXPERIMENT 1 ON INTERACTIONS BETWEEN Si AND P

Treatment	Yield (g pot^{-1})		P uptake (mg pot^{-1})		pH of topsoil	
	–P	+P	–P	+P	–P	+P
–Si	0.33	0.33	0.51	1.19	5.13	4.77
Acidulated rock silicate (ARS)	0.44	1.78	0.60	3.56	5.20	5.37
ARS + calc silicate	0.39	0.60	0.48	2.24	5.81	5.82
Lsd (*P*<0.05)	0.20		0.34		0.09	

The application of Si markedly increased the % fertilizer P recovery in the rice tops and the proportion of P in the plant derived from the fertilizer (Table 3), with the greatest increase in the ARS treatment. Conversely, the plants took up significantly less P from the soil where Si was applied in the absence of P addition (Table 3). The application of ARS significantly increased the Si uptake of the plant tops (Table 3).

TABLE 3. FERTILIZER P RECOVERY, % P IN RICE DERIVED FROM FERTILIZER AND SOIL AND Si CONCENTRATION IN RICE TOPS

Treatment	Fertilizer P recovery (% of applied)	% P in tops from fertilizer	% P in plant from soil	Si uptake in tops (mg pot^{-1})
	+P	+P	–P	+P
–Si	0.88	45.4	70.6	0.14
ARS	5.08	88.2	16.7	1.01
ARS + calc silicate	1.69	46.8	70.3	0.27
Lsd (*P*<0.05)	0.63	22.5	17.2	

[a]ARS, acidulated rock silicate

[b]SRR x 100

In the desorption study undertaken on the soil from the pots after harvest of the rice plants, the ^{32}P had decayed beyond the detection limit and so partitioning of P sources was not possible. There was no difference between treatments in the absence of applied P but significantly less P was desorbed from the ARS treatment (Table 4).

TABLE 4. PHOSPHORUS DESORBED BY 0.01 M $CaCl_2$

Treatment	P desorbed (µg ml^{-1})	
	–P	+P
–Si	0.003	0.406
Acidulated rock silicate	0.005	0.081
Acidulated rock silicate + calcsilicate	0.006	0.346
Lsd (*P*<0.05)	0.058	

3.2. EXPERIMENT 2A (P ADDITION AND SILICA SOURCE)

3.2.1. Dry matter yield and P uptake of rice tops

There was a dry matter yield response of rice tops to P addition in all treatments which received Si addition but not in the –Si treatment (Table 5). Similarly, increased P uptake was recorded in all treatments when P was applied. Addition of Si did not result in an increase in P uptake in the absence of P but when P was applied all Si sources increased P uptake to the same extent, with no significant difference between treatments. Si uptake into the plant tops was not affected by either P or Si addition (Table 5).

There was a significant increase in the % of plant P derived from the fertilizer in the unacidulated rock silicate, and the un acidulated or acidulated calcsilicate treatments. All Si treatments increased fertilizer P uptake with the greatest increase with acidulated calcsilicate (Table 5). Plant specific radioactivity (SR) of ^{32}P and ^{33}P was unaffected by addition of Si but the addition of fertilizer P reduced plant ^{32}P SR (Table 5).

TABLE 5. YIELD OF RICE TOPS AND UPTAKE OF P AND Si AS AFFECTED BY ADDITION OF P AND ACIDULATED AND UNACIDULATED ROCK SILICATE OR CALC SILICATE

Treatment	Si[a]	P	Yield	Uptake (mg pot^{-1})		Pdff[b]	Fertilizer P uptake (mg pot^{-1})	Plant SR (Bq μg P^{-1})	
			(g pot^{-1})	P	Si	(%)		^{33}P	^{32}P
Control	–	–	1.96 bcde	1.91 c	27.2		0		12.0
+ Rock Si	U		1.36 e	1.58 c	24.3				13.7
	A		1.99 cd	2.21 c	28.1				12.8
+ Calc Si	U		1.58 de	1.81 c	23.5				13.7
	A		1.75 cde	1.74 c	25.9				13.3
Control	–	+	1.63 de	2.85 b	23.6	18.3 b	0.65 c	18.5	4.6
+ Rock Si	U		2.35 abc	4.32 a	27.1	19.5 a	0.80 b	19.7	4.4
	A		2.41 ab	4.10 a	28.5	17.6 b	0.76 b	17.8	4.4
+ Calc Si	U		2.36 abc	4.50 a	30.4	19.0 a	0.79 b	19.2	4.4
	A		2.61 a	4.16 a	30.3	20.7 a	0.94 a	20.9	3.7

[a]U, unacidulated; A, acidulated

[b]Pdff, phosphorus derived from the fertilizer

Data within a column followed by the same letter are not significantly different, DMRT (*P*<0.05)

3.2.2. Soil P dynamics

Addition of P fertilizer resulted in an increase in ^{32}P activity in the soil solution at each sampling time (Table 6) indicating that the fresh addition of P displaced adsorbed P and / or stimulated the mineralization of organic P which had been labelled with ^{32}P during the equilibration period.

TABLE 6. EFFECT OF FERTILIZER P ON ^{32}P ACTIVITY (Bq ml^{-1}) IN THE SOIL SOLUTION

Days after transplanting	–P	+P
1	6.0	23.7
6	9.9	21.3
46	7.1	24.5

There were marked differences between treatments in the quantity of fertilizer P measured in the soil solution (Fig. 2). At day 1 fertilizer P in the soil solution was highest in the two calc silicate treatments, intermediate with rock silicate and low in the –Si treatment, with no difference between the + and – acid treatments. There was a dramatic reduction in fertilizer P in the soil solution between days 1 and 6 in all treatments with the greatest decline in the unacidulated calc silicate (Calsil -acid) treatment. This decline continued between days 6 and 46 in the acidulated treatments and the –Si control. By contrast there was an increase recorded in the unacidulated treatments (Fig. 2).

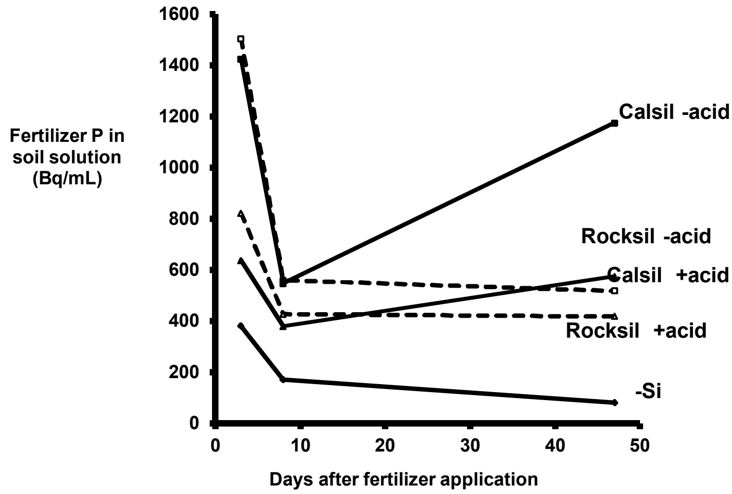

FIG. 2. Effect of addition of acidulated (+acid) and un-acidulated (-acid) rock silicate and calc silicate on fertilizer P concentration in the soil solution over time.

3.3. EXPERIMENT 2 (FLOODING AND ARS)

3.3.1. Dry matter yield and P uptake of rice tops

There was a dry matter response to P in all treatments, except where ARS was not applied, and pre flooding resulted in a lower dry matter yield of rice tops than where the soil had not been flooded (Table 7). Addition of ARS increased dry matter yield and P uptake of rice tops under unflooded conditions, but not where the soil had been pre flooded (Table 7). Si uptake was not affected by either ARS addition or soil water conditions. Addition of ARS under unflooded conditions increased fertilizer P uptake but not the % of P in the plant derived from the fertilizer (Table 7). Addition of ARS increased the recovery of fertilizer P in the tops from 0.53% to 0.80% but did not alter the P uptake from the native soil P as indicated by the SRR data. Pre flooding the soil increased the % of P in the plant derived from the fertilizer, but there was a lower fertilizer P uptake and recovery of fertilizer P in the plant. Uptake of native soil P, as indicated by the lower SRR value, was higher in the pre flooded than the unflooded treatment in the presence of ARS (Table 7).

TABLE 7. YIELD OF RICE TOPS AND P DYNAMICS AS AFFECTED BY APPLICATION OF ACIDULATED ROCK SILICATE (ARS) AND PRE FLOODING

Treatment[a]	Yield (g pot^{-1})	Uptake (mg pot^{-1})		Pdff[b] (%)	Fertilizer P in plant		SRR[c]	SR plant (Bq µg P^{-1})	
		P	Si		(mg pot^{-1})	(%)		^{33}P	^{32}P
+P –Si (U)	1.63 b	2.9 b	23.6	18.3 b	0.65 b	0.53 b	0.39a	18.5 b	4.6 a
+P+ARS (U)	2.41 a	4.1 a	28.5	19.5 b	0.80 a	0.80 a	0.37a	19.7 b	4.4 a
+P+ARS (PF)	2.00 ab	2.8 b	28.0	23.3 a	0.66 b	0.66 b	0.15b	23.4 a	1.8 b
Lsd (P<0.05)	0.58	0.9	ns	2.7	0.12	0.20	0.12	2.7	1.5

[a]ARS, acidulated rock silicate; U, unflooded; PF, pre flooded

[b]Pdff, phosphorus derived from the fertilizer

[c]Lower values mean a higher proportion of P in the plant from the native soil P

Data within a column followed by the same letter are not significantly different, DMRT (P<0.05)

3.3.2. Soil solution

Measurements made on the activity in the soil solution at 1, 6 and 46 days after application showed marked differences between treatments and over time (Fig. 3).

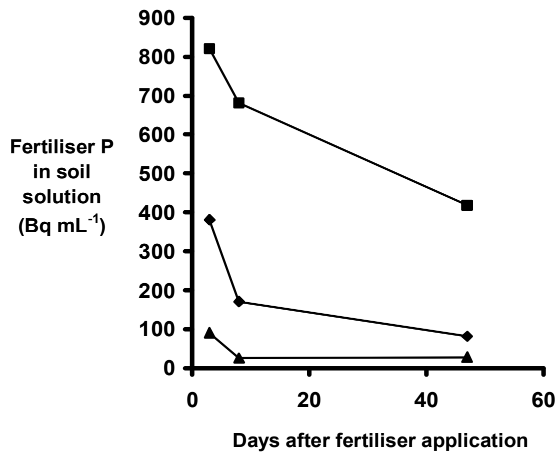

FIG. 3. Effect of Si addition and prior soil water conditions on fertilizer P in the soil solution at 1, 6 and 46 days

Pre flooding dramatically reduced the concentration of fertilizer P in the soil solution (+P+ARS, pre flooded cf. +P +ARS, unflooded) and the addition of oxidised rock silicate increased the fertilizer P concentration in the soil solution (+P –ARS, unflooded cf. +P +ARS, unflooded). In all three treatments there was a marked decline in the fertilizer P concentration in the soil solution over time (Fig. 3).

3.4. EXPERIMENT 3 (ADSORPTION AND DESORPTION STUDIES)

3.4.1. First experiment

The main result of this study was the high amount of P adsorption onto all studied Si materials (Table 8). The percentage of P adsorbed was lower and the % of P desorbed higher in the rock silicate oxidized at high temperature (800°C) compared to the rock silicate oxidized at low temperature, which had been heated to 200°C. The amount desorbed from each of the two Si sources over four desorption cycles ranged from 13.4 to 33.8% of that adsorbed with the lower P sorbing rock silicate oxidized at high temperature releasing more P than the rock silicate oxidized at low temperature.

TABLE 8. AMOUNT OF P ADSORBED FROM THREE Si SOURCES AND SUBSEQUENTLY DESORBED IN FOUR DESORPTION CYCLES

Rock silicate	Initial P (μg g^{-1} soil)		Adsorption (%)	Desorbed (μg g^{-1} soil) at day:				Desorbed / adsorbed (%)
	Added	Adsorbed		0	9	16	24	
Unoxidized	500	490	98.0	6	10	51	47	23.3
	1000	978	97.8	8	11	49	64	13.4
High temperature oxidized	500	438	87.6	46	19	29	54	33.8
	1000	767	76.7	67	34	44	28	22.5
Low temperature oxidized	500	490	98.0	5	5	24	49	16.9
	1000	933	93.3	38	38	42	22	15.1

3.4.2. Second experiment

In this experiment the acidulation of rock silicate resulted in an almost fivefold increase in P sorption (Table 9). The addition of lime and acid to the rock silicate reduced P sorption slightly but increased the desorption of the adsorbed P.

TABLE 9. EFFECT OF ACID AND LIME ADDITION TO ROCK SILICATE ON P SORPTION AND DESORPTION

Treatment		P sorbed (%)	P desorbed (%)
Acid	Lime		
–	–	22.5	32.5
+	–	99.6	0.2
+	+	98.8	4.4

4. DISCUSSION

These series of experiments have shown that fertilizer P dynamics in soil can be altered by intimately mixing the fertilizer with modified silica minerals. The enhanced fertilizer P recovery by the plants appears to be related to adsorption / desorption reactions on the modified silica surfaces rather than mono-silicic acid blocking P adsorption sites.

Mono-silicic acid is known to be adsorbed onto iron and aluminium oxide surfaces and there in a great deal of conjecture as to whether such adsorption competes with the adsorption of P. This is particularly important in the rice–wheat system where soil redox related to changes from flooded (reduced) to non-flooded (oxidized) conditions as wheat follows rice. During this process soluble ferrous phosphate transforms into insoluble ferric phosphate, whilst mono-silicic acid remains adsorbed or in solution at soil pH lower than approximately 9.0.

While P from the soluble ferrous phosphate is readily available to the rice crop the ferric phosphate formed under aerobic conditions can become precipitated or strongly adsorbed to colloid surfaces, which substantially reduces its availability to the wheat crop. If mono-silicic acid is preferentially adsorbed to these surfaces than phosphate then this could be used to reduce the amount of P to be applied to the wheat phase of the rotation.

Early research showed that residual concentrations of mono-silicic acid in a range of Australian soils were controlled by a sorption equilibrium, which was dependent on pH [8]. It was also found that mono-silicic acid was adsorbed to montmorillonite and sesquioxide surfaces and it was postulated that the reaction occurring at oxide surfaces was similar to that of iron and polysilicates [8].

Independent studies conducted in Canada showed strong adsorption of mono-silicic acid from dilute solutions onto freshly precipitated hydroxides of polyvalent metal ions [9]. By contrast, adsorption was weaker onto soil particles and iron oxide surfaces and there was no adsorption onto alkaline-earth carbonate minerals. It was found that the adsorption data approximately conformed to Freundlich's adsorption isotherm [9]. Adsorption of mono-silicic acid increased over the pH range 4 to 9, and with the ferruginous soil, adsorption decreased as the pH was increased above 10. These data support the Australian data [8] that a pH dependent adsorption reaction is involved in controlling the concentration of silica in the soil solution. These early studies were confirmed in a later study [10]. In a review of Si in soils, plants and animals [11] the importance of iron and aluminium oxides in controlling the soil solution concentration of Si was highlighted. These same oxides are largely responsible for controlling soil solution P concentrations in acid soils.

The scope of this project did not include the study of this proposition but earlier studies suggest that residual mono-silicic acid that would likely result from the addition of ARS could have this effect. This aspect is worthy of further study.

The mode of action of ARS in increasing P use efficiency appears to be the weak adsorption of P onto the surface of the ARS and its gradual desorption into the soil solution. The process appears to compete with P adsorption onto soil colloid surfaces. Early research conducted at Rothamsted found that the beneficial effect of Si was larger when P was not supplied and this was believed to be due to either a partial substitution of Si for P within the plant or in Si making P more available in the soil. Plant P and Si data from the experiments reported here do not support this proposition. Addition of silicate materials did not increase Si uptake. No evidence has been found that Si increased P uptake [12, 13]. The difficulty in interpreting these earlier studies is that it was not possible to distinguish between native and added sources of Si and P because isotopes were not used.

Using ^{29}Si NMR it was found that concentrated acidic silicate solutions contained many different types of silicate anions in dynamic equilibrium [14]. This indicates the complexity of studying silicon interactions in the soil solution without the aid of isotopes. In addition to silicon being present in inorganic forms in the soil solution, silicates have a high affinity to terminal carboxylate groups and as such organo silicates could be important in soil solutions [15].

It has been claimed [16] that Si research has been hampered by the lack of a suitable radioactive isotope of Si, as ^{31}Si has a half-life of 2.62 h. Therefore experiments were conducted with a cognate isotope ^{68}Ge in an attempt to overcome the problem [16]. While it appeared that Ge could be used as a surrogate for Si in uptake studies, the Ge taken up was toxic to plants. In fact, Si has three stable isotopes ^{28}Si, ^{29}Si and ^{30}Si at natural abundances of 92:2, 4.7 and 3.1 atom %, respectively. ^{30}Si-labelled silicic acid has been used in studies of Si uptake by marine phytoplankton [17] and Si adsorption in soil [18]. ^{30}Si is commercially available in the form of SiO_2.

5. CONCLUSIONS

A series of pot and laboratory experiments were conducted to examine the effect of additions of silica minerals on fertilizer P reactions in soils and rice growth. Addition of acidulated rock silica (ARS) with fertilizer P increased the growth of rice tops more than fivefold and increased the fertilizer P recovered in the tops from 0.88 to 5.08%.

In a second experiment the growth response was not as large but yield and fertilizer P uptake responses to unacidulated RS and ARS and calc silicate were recorded. In a third experiment pre-flooding of the soil resulted in an eight-fold reduction in the concentration of fertilizer P in the soil solution compared to the non-flooded soil. The addition of ARS increased the yield of rice tops and total and fertilizer P uptake in both flooding treatments with the % of fertilizer P in the plant higher in the pre flooded (23.3%) compared to the unflooded (19.5%) soil.

Two P adsorption studies showed that ARS adsorbs P, one third of which can be desorbed over 24 days. The results indicate that addition of ARS with P fertilizer to a rice crop grown in a non-flooded soil or a non-flooded crop grown after a flooded crop, as in a rice–wheat rotation, can substantially improve yields and P use efficiency. Further research is needed to confirm these results in field studies. The degree and process of acidulation of rock silicates requires considerably more research and the combined use of ^{32}P and ^{30}Si will greatly assist this research.

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^{15}N AIDED STUDIES TO ASSESS THE NITROGEN USE EFFICIENCY IN INTENSIVELY CULTIVATED RICE–WHEAT CROPPING SYSTEMS IN ASIA AND AUSTRALIA

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Abstract

In the frame of the FAO/IAEA Co-ordinated Research Project on Integrated Soil, Water and Nutrient Management for Sustainable Rice–wheat Cropping Systems in Asia (2002–06), a series of ^{15}N-aided field experiments were conducted to investigate the impacts of novel crop establishment techniques on fertilizer N use efficiency (NUE) in intensive rice–wheat cropping systems. The use of ^{15}N allowed for the tracing of the N through the system and quantification of fertilizer N recovery in plants and soil, and the calculation of the amount of fertilizer N which had been lost from the soil–plant system. In the first set of experiment on the impacts of crop establishment methods on the fate of ^{15}N labelled urea in rice and the subsequent wheat crop at four locations, fertilizer N was more prone to losses in raised beds and zero till rice (non-flooded systems) than the conventional flooded rice system. In a second set of experiments on the recovery and balance of ^{15}N labelled urea in flooded and

aerobic rice–based cropping systems at two locations in China, the aerobic rice–wheat system was less efficient in NUE than the conventional flooded rice system. In a third set of experiments on the fertilizer N efficiency of NH_4^+ and NO_3^- based fertilizers in a rice–wheat rotation in Sichuan, China, regardless of the crop water regime (flooded or aerobic), more NH_4^+-N was recovered by the crops than NO_3^--N; and more residual NH_4^+-N than NO_3^--N was found in the soil. The resulting losses (unaccounted for) for NH_4^+-N were significantly less than with NO_3^--N. In a fourth set of experiments on the timing of application of ^{15}N labelled urea to irrigated rice grown in permanent beds in Griffith, Australia, two and three split applications of urea at 150 kg N ha^{-1} improved NUE when compared to a single application in furrow irrigated rice grown in permanent raised beds. In a fifth set of experiments on methods for determining NUE in Ludhiana, India and Nanjing, China, fertilizer N recovery values were lower using the isotopic method RE_{N15} compared to the non-isotopic (difference) method RE_N. Overall, the results indicate that there is great scope to improve NUE in rice–wheat cropping systems grown with novel crop establishment methods. Further research in long term field experiments using an integrated approach to soil, water and nutrient management should be carried out to improve the productivity and sustainability of rice–wheat cropping systems.

1. INTRODUCTION

Rice and wheat are intensively cultivated on over 20 million ha of land, of which some 13.5 million ha are grown in the Indo-Gangetic plains and the rest in China. The rice–wheat system is a predominant cropping system in Asia providing food, employment and income, ensuring the livelihoods of about 1 billion of resource poor rural and urban people [1]. During the past decades, yield increases have kept pace with growing populations; however, the productivity of the current rice–wheat systems is seriously threatened by increasing land degradation and scarcity of water and labour, inefficient cropping practices and other emerging socio-economic and environmental drivers. Extensive tracts of productive cropland have been taken over by rapidly growing urbanisation and related infrastructure development. These drivers combined with the impacts of climate change exacerbate the pressures on the sustainable agricultural production in the agro-ecosystems of the Asian region [2].

Crop yields are decreasing in many areas because of soil organic matter depletion, declining soil fertility status, increasing salinization and deteriorating soil physical conditions. Conventional practices for rice–wheat include growing rice during the summer season (May–June through September–October) and wheat during the winter season (November–April) in a continuous sequence of crop rotation. Rice cultivation involves tillage of the soil in a saturated state and puddling, which destroys soil structure and can result in the formation of hard pan layers at 15–30 cm depth. When the soil dries following the rice crop, cultivation for the following wheat crop is difficult and often results in limited soil–seed contact and poor seedling emergence and reduced yields. Rice residues are often burned due to time and labour constraints for planting wheat [2]. These conventional crop establishment methods/ management practices (crop layout, planting method, tillage system, crop residue management and water regime) followed in rice–wheat systems need to be modified with adoption of resource conservation technologies for higher production, income, sustainability, resource use efficiency, and adaptation to climate change and climatic variability [1, 2]. This transformation of the irrigated rice–wheat system involves the development of alternative crop establishment methods and improved cropping practices that include elements of Conservation Agriculture aiming at producing more food at higher income levels and reduced risk, using land, labour, water, nutrients, and pesticides more efficiently than at present and mitigating adverse impacts on the local and global environment [1].

In Australia, lowland rice is grown under flood irrigation in paddies but the availability of irrigation water is decreasing while water costs are increasing. In other areas of

South Asia, water availability is also decreasing making improved water use efficiency an issue of major importance in these systems [3]. Neutron probes can be used to monitor soil water status and aid in determining crop water use and increasing water use efficiency in many cropping systems, particularly in non-flooded situations.

Soils in most of the intensively cultivated rice–wheat growing areas have low contents of soil organic matter and low nitrogen (N) availability. Fertilizer N is an essential input in rice–wheat systems to ensuring good growth and adequate yields. High inputs of fertilizer N are applied to irrigated systems and irrigation water management is a key factor influencing nitrogen use efficiency (NUE) [2, 4]. Efficient management practices for enhancing the availability of soil and fertilizer N (splitting, timing, methods and forms of application) are one of the approaches commonly used to achieving a higher economic crop yield, increased recovery efficiency of the applied fertilizer N and reducing N fertilizer loss through various means to protect land and water resources and promote environmental sustainability [4, 5, 6]. The main loss pathways for N fertilizers are leaching, denitrification and ammonia volatilization. The loss of nitrous oxide (N_2O) gas is of major importance as it is a major contributor to global warming, being 310 times more effective in trapping heat in the atmosphere than CO_2. Loss of nitrate (NO_3^-) through leaching can have severe environmental consequences particularly on the quality of drinking water. It is of great importance to optimize the availability of any added N fertilizer to crops not only because of the environmental pollution that N losses can cause but also because of the continuous increase in fertilizer prices. The prerequisite of such a management system, however, is to quantify the dynamics and losses of N at field, farm and regional scales. The use of ^{15}N labelled fertilizers can aid in quantifying plant N uptake and recovery efficiency of the applied fertilizer N in the soil–plant system. This enables an estimation of the losses of the added N fertilizer from the system and the calculation of the nitrogen use efficiency of the system [7, 8, 9].

The FAO/IAEA Co-ordinated Research Project on Integrated Soil, Water and Nutrient Management for Sustainable Rice–wheat Cropping Systems in Asia was designed to investigate the impacts of different crop establishment techniques for growing rice and wheat in these areas on crop yields, NUE and water use efficiency (WUE) [10]. The use of ^{15}N allowed for the tracing of the N through the system and quantification of fertilizer N recovery in plants and soil, and the calculation of the amount of fertilizer N which had been lost from the soil–plant system. This paper summarizes the main findings obtained in the ^{15}N-aided studies conducted to examine and improve the efficiency of the applied fertilizer N in the various experimental sites.

2. MATERIALS AND METHODS

Field experiments were set up at the following sites: Ludhiana in northwest India [11]; Meherpur, Bangladesh [12]; Ranighat, Nepal [13]; Lahore, Pakistan [14]; Sichuan [15] and Nanjing [16], China and Griffith, Australia [17]. The sites were located between the latitudes of 34.3°S (Griffith, Australia) and 33.5°N (Nanjing, China) and longitudes of 74.0–146.0°E. The altitudes ranged from 7 to 540 m above mean sea level. The mean maximum and minimum temperatures during the rice season were 26.8–34.3°C and 14.6–26.8°C, and in the wheat season were 15.4–28.0°C and 8.1–15.5°C, respectively. Average annual rainfall across the sites ranged from 88–1646 mm in the rice season and 76–884 mm in the wheat season.

In terms of soil fertility the sites varied widely with soil organic C concentration ranging from 4.5–12.0 g kg^{-1}, total N from 0.4–1.7 g kg^{-1} and pH from 5.8–8.4. Textural classes of the experimental soils were sandy loam to clay. Detailed descriptions of the experimental sites and field and crop management treatments can be found in the corresponding chapters of this volume.

All the field experiments used ^{15}N labelled fertilizer in micro plots, for studying the impact of integrated crop establishment and management practices, water and fertilizer management on fertilizer N recovery efficiency (RE_{N15}) and balance in rice–wheat cropping systems. Unless otherwise specified, in most experiments ^{15}N labelled urea (5 atom % ^{15}N) was the isotopically labelled fertilizer N source.

The following fertilizer N management studies were conducted in the frame of the FAO/IAEA Co-ordinated Research Project on Integrated Soil, Water and Nutrient Management for Sustainable Rice–wheat Cropping Systems in Asia (2002–06):

2.1. IMPACTS OF CROP ESTABLISHMENT METHODS ON THE FATE OF ^{15}N LABELLED UREA IN RICE AND SUBSEQUENT WHEAT CROP IN THE INDO-GANGETIC PLAINS

At the sites in Ludhiana, India [11], Meherpur, Bangladesh [12], Ranighat, Nepal [13] and Lahore, Pakistan [14], the field experiments studied the effects of using permanent raised beds under aerobic conditions with either transplanted or direct seeded rice followed by direct seeded wheat and compared the results to conventional flooded systems with transplanted seedlings and conventional cultivation before sowing wheat. A system of zero till rice and wheat was also studied.

2.2. RECOVERY AND BALANCE OF ^{15}N LABELLED UREA IN FLOODED AND AEROBIC RICE-BASED CROPPING SYSTEMS IN CHINA

The field experiments in Sichuan, China [15] and Nanjing, China [16] investigated the effect of using water-saving techniques, i.e. aerobic (well-watered aerated) rice cultivation with either plastic or straw mulch which was compared to conventional flooded systems.

2.3. FERTILIZER N EFFICIENCY OF NH_4^+ AND NO_3^- BASED FERTILIZERS IN RICE–WHEAT

At Sichuan, China [15], the NUE from ammonium and nitrate-based fertilizers were assessed using ^{15}N labelled fertilizers {ammonium sulphate (9.8 atom % ^{15}N) and potassium nitrate (10 atom % ^{15}N)} in a rice–wheat crop rotation.

2.4. TIMING OF ^{15}N LABELLED UREA APPLIED TO FURROW IRRIGATED RICE GROWN IN PERMANENT BEDS IN AUSTRALIA

The field experiment in Griffith, Australia [17] investigated the N dynamics in permanent raised beds using ^{15}N labelled urea at various N rates and split applications compared to a single application.

2.5. COMPARISON OF METHODS FOR DETERMINING NUE IN INDIA AND CHINA

In the experiments at Ludhiana, India [11] and Nanjing, China [16] two methods were used to determine NUE in rice–wheat cropping systems, i.e. the non-isotopic difference method (apparent recovery of fertilizer N, REN) and the ^{15}N isotopic method (isotopic fertilizer N recovery efficiency, RE_{N15}).

Detailed descriptions of the experimental design and management of the field experiments can be found in the respective chapters of the CRP participants, this volume.

Plant and soil (to a known depth) samples were collected at harvest time and processed. Subsamples were analysed for total N and N isotope ratio using an Elemental Analyser coupled to an Isotope Ratio Mass Spectrometer (IRMS) at the IAEA’s Seibersdorf

Laboratory. Calculation of the parameters to evaluate NUE, i.e. fertilizer N recovery in plant and soil and balance of applied fertilizer was made according to standard procedures [9].

3. RESULTS AND DISCUSSION

3.1. IMPACTS OF CROP ESTABLISHMENT METHODS ON THE FATE OF ^{15}N LABELLED UREA IN RICE AND THE SUBSEQUENT WHEAT CROP IN THE INDO-GANGETIC PLAINS

Conventional puddled, flooded rice was compared with raised beds and zero till rice (non-flooded) in field experiments at four locations in the IGP. The summary data on the fate of the applied ^{15}N labelled urea to rice in these locations (Table 1) show the following:

a) Rice recoveries were higher in the high annual rainfall (above 1000 mm) locations (Meherpur, Bangladesh and Ranighat, Nepal) fertilized with 100 kg N ha^{-1} compared to those from semiarid environments (300–600 mm) where rice is mainly grown under irrigation (Lahore, Pakistan and Ludhiana, India) fertilized at 120 kg N ha^{-1}. It should be noted that these results may be also related to the different rates of applied N. It is reported that crop recoveries will normally decrease with increasing fertilizer N rates because of the increased chances for N losses.

b) In contrast, the recovery data in the soil indicated that more residual N (about twofold) was found in the soil from the locations from semiarid environments compared to those in high rainfall locations.

c) Losses of fertilizer N estimated by mass balance were high for all locations (36–55%).

TABLE 1. FATE OF ^{15}N LABELLED UREA IN RICE GROWN UNDER FLOODED AND NON-FLOODED CONDITIONS IN ASIA

Location	N rate (kg ha^{-1})	Establishment method	Recovery (% of applied N)			
			Crop	Soil	Crop + soil	N loss
Meherpur, Bangladesh	100	Flooded	33.5	13.7	47.2	52.8
		Non-flooded	31.3	14.2	45.5	54.5
Ranighat, Nepal	100	Flooded	45.8	18.5	64.3	35.7
		Non-flooded	36.2	16.0	52.2	47.8
Ludhiana, India	120	Flooded	29.9	32.5	62.4	37.6
		Non-flooded	16.2	29.1	45.3	54.7
Lahore, Pakistan	120	Flooded	27.7	27.0	54.7	45.3
		Non-flooded	21.6	31.0	52.6	47.4
Bangladesh and Nepal	100	Flooded	33.5–45.8	13.7–18.5	47.2–64.3	35.7–52.8
		Non-flooded	31.3–36.2	14.2–16.0	45.5–52.2	47.8–54.5
		Mean	36.7	15.6	52.3	47.7
India and Pakistan	120	Flooded	27.7–29.9	27.0–32.5	54.7–62.4	37.6–45.3
		Non-flooded	16.2–21.6	29.1–31.0	45.3–52.6	47.4–54.7
		Mean	23.9	29.9	53.8	46.2

In comparing NUE in rice as influenced by crop establishment methods (Table 1), the results show:

a) In all locations crop recoveries were higher in the conventional puddled, flooded rice than in raised beds and zero till rice.

b) Recovery data from fertilizer in soil were similar for the crop establishment methods (flooded and non-flooded).

c) Losses (unaccounted for N) were higher in the raised beds and zero till rice system (47–55%) than in the conventional puddled, flooded rice (36–53%) in all locations.

The summary data on the fate of the applied ^{15}N labelled urea to the subsequent wheat crop in these locations (Table 2) were as follows:

a) Wheat recoveries were very variable in the studied locations. The lowest recoveries were found in Meherpur, Bangladesh (16–20%), intermediate in Ludhiana, India (24–31%), and highest in Ranighat, Nepal and Lahore, Pakistan (33–37%).

b) Similarly, the recovery data in the soil were also variable. They ranged from 18–29% in Ludhiana, India and Lahore, Pakistan, and up to 47–51% in Meherpur, Bangladesh and Ranighat, Nepal.

c) Losses (unaccounted for N) were also variable. The average lowest losses were found in Ranighat, Nepal (16%), intermediate in Lahore, Pakistan and Meherpur, Bangladesh (34–37%), and highest in Ludhiana, India (51%).

TABLE 2. FATE OF ^{15}N LABELLED UREA (120 kg N ha^{-1}) IN WHEAT GROWN AFTER RICE UNDER FLOODED AND NON-FLOODED CONDITIONS IN ASIA

Location	Establishment method	Recovery (% of applied N)			
		Crop	Soil	Crop + soil	N loss
Meherpur, Bangladesh	Flooded	20.2	48.9	69.1	30.9
	Non-flooded	16.1	46.5	62.6	37.4
Ranighat, Nepal	Flooded	35.8	50.7	86.5	13.5
	Non-flooded	32.8	49.4	82.2	17.8
Ludhiana, India	Flooded	31.1	17.8	48.9	51.1
	Non-flooded	24.4	24.4	48.8	51.2
Lahore, Pakistan	Flooded	37.1	27.7	64.8	35.2
	Non-flooded	32.6	29.2	61.8	38.2
All locations	Flooded	20.2–37.1	17.8–50.7	48.9–86.5	13.5–51.1
	Non-flooded	16.1–32.8	24.4–49.4	48.8–82.2	17.8–51.2

In comparing NUE in wheat as influenced by crop establishment methods (Table 2), the results show:

a) In all locations wheat recoveries ranged from 16–37%. They were higher in wheat grown after the conventional puddled, flooded rice than in raised beds and zero till systems.

b) Recovery data from fertilizer in soil were similar for the crop establishment methods in the high rainfall locations. In the irrigated, semiarid environments wheat grown in raised beds had more residual N than wheat grown after conventional flooded rice.

c) Losses (unaccounted for N) were similar for crop establishment methods in Ludhiana, India but in general in the other locations they were slightly higher in the wheat grown in raised beds and zero till systems than in wheat after the conventional puddled, flooded rice in the other locations.

The data indicate that fertilizer N applied as urea is more prone to losses in raised beds and zero till rice (non-flooded systems) than the conventional flooded rice system. These results are in contrast to the reports that the adoption of resource conserving technologies can increase NUE and that of water and energy in rice–wheat systems [1]. It is reported that lowland rice varieties are sensitive to moderate water deficits [18]. In other studies it has been also found that raised beds have limited potential with current technology due to the occurrence of several constraints to crop yields [2].

There is a need to develop further technologies for growing rice in raised beds, including suitable cultivars and improved fertilizer N and irrigation water management practices to further improve NUE in these non-flooded systems.

3.2. BALANCE OF ^{15}N LABELLED UREA IN FLOODED AND AEROBIC RICE-BASED CROPPING SYSTEMS IN SICHUAN AND NANJING, CHINA

In China, the studies at two locations focused on the influence of water saving technologies such as aerobic rice with plastic or straw mulching on the fate of ^{15}N labelled urea in rice–based systems (Table 3).

TABLE 3. FATE OF ^{15}N LABELLED UREA IN FLOODED AND AEROBIC RICE BASED CROPPING SYSTEMS IN CHINA

Location	N rate	Crop	Recovery (% of applied N)			
	(kg ha^{-1})	management	Crop	Soil	Crop + soil	N loss
Sichuan	180	Flooded rice	23.3	35.2	58.5	41.5
		Aerobic rice	26.2	19.2	45.4	54.6
	120	Wheat after flooded rice	43.9	38.0	81.9	18.1
		Wheat after aerobic rice	36.5	34.5	71.0	29.0
Nanjing	180	Flooded rice	29.4	28.2	57.6	42.4
		Aerobic rice	25.6	28.2	52.6	47.4
	120	Barley after flooded rice	20.6	42.2	62.8	37.2
		Barley after aerobic rice	26.2	39.2	65.4	34.6

At Sichuan the results in the rice–wheat cropping system were as follows:

a) Higher recoveries of urea-N and thus less N losses were found in the wheat crop (37–44%) than in the rice crop (23–26%).

b) In the rice crop, fertilizer N recoveries were similar (23–26%), the recovery in soil was 1.8 fold higher in the flooded than in the aerobic system and the losses were 1.3 fold greater in the aerobic system.

c) In the wheat sequential crop, fertilizer N recovery was 1.7 fold greater in wheat after flooded rice than in wheat after aerobic rice, recoveries in the soil were similar (35–38%) and the resulting losses were 1.6 fold higher in the wheat after aerobic rice.

From the above, it may be concluded that the aerobic rice–wheat system is less efficient in NUE than the conventional flooded rice system.

At Nanjing the data from the rice–barley system showed that both systems were similar in NUE. The rice systems showed higher crop recoveries (26–29%) but also relatively higher N losses (42–47%). The barley systems had lower crop fertilizer N recoveries (21–26%), higher soil residual N (39–42%) and less N losses (35–37%). These results indicate that the rice–barley recoveries are in general low and fertilizer N losses are high.

The results from the experiments at both sites suggested that irrigation water management is a critical factor in determining NUE in the aerobic system. Further work needs to be done to increase NUE in the aerobic systems, in particular that of the rice crop [3, 18].

3.3. FERTILIZER N EFFICIENCY OF NH_4^+ AND NO_3^- BASED FERTILIZERS IN A RICE–WHEAT ROTATION, SICHUAN, CHINA

The fate of different types of fertilizer N (NH_4^+-N and NO_3^--N forms) in a flooded/ aerobic rice–wheat crop rotation is shown in Table 4. Rice recovered significantly more NH_4^+-N than NO_3^--N under flooded conditions but there was a similar recovery from both N forms under aerobic (non-flooded) conditions. More residual NH_4^+-N was also recovered in the soil under flooded and aerobic conditions, thus resulting in significantly lower losses with NH_4^+-N than NO_3^--N. These effects were more pronounced with conventional flooded rice due to the higher uptake from NH_4^+-N and NO_3^--N than non-flooded rice, but soil residual N was similar, and thus the N losses in flooded rice were less (30–45%) than that in aerobic (non-flooded) rice (42–48%). More losses were found with the NO_3^--N (45–48%) than NH_4^+-N (30–42%).

In wheat grown after rice the recovery of NH_4^+-N was significantly greater (35–40%) than NO_3^--N (31–32%) under both flooded and non-flooded conditions (Table 4). Recovery of NH_4^+-N or NO_3^--N in soil was similar between the flooded non-flooded treatments. Estimated N loss was significantly lower with NH_4^+-N (28–30%) than NO_3^--N (35–40%). N losses were higher with wheat after flooded rice (30–39%) than wheat after aerobic rice (28–35%).

TABLE 4. FATE OF ^{15}N LABELLED NITROGEN SOURCES (AMMONIUM-N AND NITRATE-N) IN A RICE–WHEAT CROP ROTATION, SICHUAN, CHINA

Crop/water regime	N rate (kg ha^{-1})	N source	Recovery (% of N applied)			
			Crop	Soil	Crop + soil	N loss
Flooded rice	180	NH_4^+	34.4	35.6	70.0	30.0
		NO_3^-	24.5	30.4	54.9	45.1
Aerobic rice	180	NH_4^+	26.5	31.8	58.3	41.7
		NO_3^-	25.1	27.1	52.2	47.8
Rice (average)		NH_4^+	30.5	33.7	64.2	36.8
		NO_3^-	24.8	28.8	53.6	46.4
Wheat after flooded rice	120	NH_4^+	40.1	30.2	70.3	29.7
		NO_3^-	32.4	28.6	61.0	39.0
Wheat after aerobic rice	120	NH_4^+	35.3	36.7	72.0	28.0
		NO_3^-	30.8	34.5	65.3	34.7
Wheat (average)		NH_4^+	37.7	33.5	71.2	28.8
		NO_3^-	31.6	31.6	63.2	36.8

Regardless of the crop water regime, more NH_4^+-N was recovered by the crops than NO_3^--N, and more residual NH_4^+-N than NO_3^--N was found in the soil. The resulting loss for NH_4^+-N was significantly less than with NO_3^--N. These results are in agreement with past reports that ammonium was the predominant form of N under flooded conditions and the preferred form of N for lowland rice grown under these conditions [7, 8]. Nitrate is more prone to losses by downward movement in the soil and denitrification. However, as the crop fertilizer N recoveries were low (25–31% for rice and 32–38% for wheat) and consequently the fertilizer N losses from the soil-plant system were high (37–47% for rice and 29–37% for wheat), there is scope for further increasing NUE by effective fertilizer N and water management, in particular in the novel rice aerobic system.

3.4. EFFECT OF SPLIT APPLICATION TIME ON THE FATE OF ^{15}N LABELLED UREA FOR IRRIGATED RICE GROWN IN PERMANENT BEDS IN GRIFFITH, AUSTRALIA

Table 5 summarizes the main results from the two year experiments on the fate of ^{15}N labelled urea applied to irrigated rice grown in permanent beds at the field site of Griffith, Australia. In the first year experiment, crop recovery was 40% for the split application compared to 28% in the single treatment. Recovery of fertilizer N in the soil (0–70 cm) was almost similar (26–28%) in both treatments. The majority of the ^{15}N labelled fertilizer was found in the top 10 cm (20–21% of the applied N). Less than 1% was found in the weeds in both treatments. Total fertilizer N recovery (crop + soil) was significantly higher in the split treatment (68%) than that of the single application (56%). Estimated losses in the split treatment were 32% (about one third of the applied N) compared to 46% (about one half of the applied N) for the single application [17]. At this site, rice yields in the ^{15}N micro plots were compared to those in the main plots. Except for one treatment where the yield in the micro plot was inexplicably higher, the differences between the yields for the micro plots and the main plots were not more than 10%.

TABLE 5. INFLUENCE OF SPLIT APPLICATION ON THE FATE OF ^{15}N LABELLED UREA (150 kg N ha^{-1}) IN IRRIGATED RICE GROWN IN PERMANENT BEDS, GRIFFITH, AUSTRALIA

Year	N application method	Recovery (% of applied N)			
		Crop	Soil	Crop + soil	N loss
First	Single	28.0	26.0	54.0	46.0
	Two split	40.0	28.0	68.0	32.0
	Lsd (*P*<0.05)	6.0	ns	12.0	
Second	Single	18.2	36.0	54.2	45.8
	Two split	33.9	41.9	75.8	24.2
	Three split	35.1	37.9	73.1	26.9
	Lsd (*P*<0.05)	7.5	ns	13.5	
Mean	Single	23.0	31.0	54.0	46.0
	Two split	37.0	35.0	72.0	28.0

Lsd, least significant difference; ns, not significant

In the second year experiment, crop recovery was 34–35% for the split application treatments compared to 18% for the single application. Recovery of fertilizer N in the soil (0–70 cm) was similar (36–42%) for all treatments. The majority of the ^{15}N labelled fertilizer was found in the top 10 cm (20–29% of the applied N). About 4% of the applied N was recovered in the 10–20 cm layer and between 1.6 and 2.4% of the applied N was found at deeper soil layers down to 70 cm. Total fertilizer N recovery (crop + soil) was significantly higher in the split treatment (73–76%) than that for the single application (54%). Estimated losses in the split treatments were 24–27% (about one quarter of the applied N) compared to 46% (about one half of the applied N) for the single application.

These results are in line with the findings from other studies carried out in the region for direct seeded rice on the flat paddy with permanent flooding after the 3 leaf stage, where crop recovery of 35% was reported for urea applied at 70 and 140 kg N ha^{-1}, while other authors have reported crop recoveries of 35–40% and losses of 25% in southern Australia [19]. Other authors reported a fertilizer N recovery of 32% by aerial sown rice in puddled soil [20].

The experiments at Griffith, Australia showed that split applications of urea at 150 kg N ha^{-1} improved NUE when compared to a single application in rice grown in permanent raised beds. As there was no significant difference between the split application treatments, the two split application at the 3 leaf stage and panicle initiation (3L + PI) may be recommended for this location.

3.5. COMPARISON OF METHODS FOR DETERMINING NUE IN LUDHIANA, INDIA AND NANJING, CHINA

At both locations results showed that fertilizer N recovery values were lower using the isotopic method (RE_{N15}) compared to the non-isotopic (difference) method, RE_N (Table 6).

TABLE 6. MEAN APPARENT (N DIFFERENCE) AND ^{15}N FERTILIZER RECOVERY IN RICE–BASED CROPPING SYSTEMS

Location	N rate (kg ha^{-1})	Treatment	Crop	Recovery (% of applied N)	
				Apparent (RE_N)	^{15}N (RE_{N15})
Ludhiana, India	120	Flooded	Rice	50.3 (168)	29.9 (100)
		Non-flooded		35.1 (217)	16.2 (100)
	120	Flooded	Wheat	67.5 (189)	35.8 (100)
		Non-flooded		59.8 (182)	32.8 (100)
Nanjing, China	180	Flooded	Rice	32.0 (109)	29.4 (100)
		Aerobic		32.9 (129)	25.6 (100)
	120	Flooded	Barley	36.8 (179)	20.6 (100)
		Aerobic		43.9 (168)	26.2 (100)

Data within parentheses are per cent with respect to RE_{N15}

These measurements were made at the research plot level and considering total biomass produced (straw and grain). In the literature there are contrasting reports on the performance of methods to obtain accurate estimates of NUE. Each has advantages and limitations. Both methods have been found to be statistically related. When using the difference method no distinction can be made between native soil N and fertilizer N, which means that NUE can often be overestimated and losses under-estimated. With regard to the isotopic method it has been reported that added N interactions such as soil pool substitution can lead to under-estimation of the amount of ^{15}N accumulated by the crop [21]. While some authors postulate that the difference method is more reliable, others reported that the isotopic method provides a more accurate estimate of fertilizer NUE.

Mean fertilizer N recoveries in rice and wheat grain of 39 and 49% (RE_N method) and of 32 and 39% (RE_{N15} method) were reported in south Asia, respectively [21]. The values may be greater when based on total biomass produced (straw + grain). On the other hand it should be noted that higher mean RE_N values can be obtained in research plots (49% and 45%) for irrigated rice and wheat, respectively, than those achieved at the farm level [5]. In general the fertilizer N recovery efficiency values obtained in the experiments are within the range of reported mean values for rice and wheat. The RE_N at Ludhiana are somewhat higher values.

The relative differences in the recovery methods for rice were greater in Ludhiana, India than those in Nanjing, China. At Ludhiana RE_N was 68–117% higher than RE_{N15} data compared to 9–29% in Nanjing, China. In both locations the differences in the recovery data for flooded rice were relatively smaller than those for non-flooded/aerobic rice.

In Ludhiana, India recovery efficiency data by both methods in wheat was higher than that of rice while in Nanjing, China they were similar. The recovery data by wheat in Ludhiana by both methods were higher than those of barley in Nanjing, China. At Ludhiana, RE_N was 82–89% higher than RE_{N15} data compared to 68–79% in Nanjing, China. In both locations the recovery data for wheat or barley after flooded rice and in Nanjing, for non-flooded aerobic rice were similar.

The relative differences between methods (isotopic and non-isotopic) were greater in wheat and barley and non-flooded aerobic rice. i.e. more aerobic conditions. This may indicate that the dynamics of N transformations are much higher under non-flooded soil conditions (alternating dry and wet cycles and related redox potential changes and microbiological transformations). These results emphasise the importance of soil physical conditions and irrigation water management on the NUE of rice–wheat systems where continuous changes occur from flooded (anaerobic) to non-flooded (aerobic) conditions during the rice growing season, and between crop seasons (rice–wheat). More effort should be made to improve the yield potential of rice grown under aerobic conditions to increase NUE [18].

4. CONCLUSIONS

A series of ^{15}N-aided field experiments were conducted to investigate the impacts of different crop establishment techniques on fertilizer NUE in intensive rice–wheat cropping systems.

In a first set of experiment at four locations in the Indo-Gangetic Plains, fertilizer N applied as urea was more prone to losses in raised beds and zero till rice (non-flooded systems) than the conventional flooded rice system. There is a need to develop suitable fertilizer N management practices to improve NUE in these non-flooded systems.

In a second set of experiments on the recovery and balance of ^{15}N labelled urea in flooded and aerobic rice–based cropping systems at Sichuan and Nanjing in China, the aerobic rice–wheat system was less efficient in NUE than the conventional flooded rice system. More effort needs to be made to increase NUE in the aerobic systems, in particular the rice crop.

In a third set of experiments on the NUE of NH_4^+ and NO_3^- based fertilizers in a rice–wheat rotation in Sichuan, China, more NH_4^+-N was recovered by the crops than NO_3^--N regardless of the crop water regime (flooded or aerobic), and more residual NH_4^+-N than NO_3^--N was found in the soil. The resulting losses (unaccounted for N) for NH_4^+-N was significantly less than with NO_3^--N.

In a fourth set of experiments on the timing of ^{15}N labelled urea applied to furrow irrigated rice grown in permanent beds in Griffith, Australia, two or three split applications of urea at 150 kg N ha^{-1} improved NUE when compared to a single application. As there was no significant difference between the split application treatments, the two split application at the 3 leaf stage and panicle initiation (3L + PI) may be recommended for this location.

In a fifth set of experiments on comparing methods for determining NUE in Ludhiana, India and Nanjing, China, fertilizer N recovery values in rice–wheat systems were lower using the isotopic method (RE_{N15}) compared to the non-isotopic (N difference) method (RE_N). These results may confirm the importance of soil physical conditions and irrigation water management on the NUE of rice–wheat systems where continuous changes occur from flooded (anaerobic) to non-flooded (aerobic) conditions during the rice growing season and between crop seasons (rice–wheat).

Overall, the results indicate that there is great potential to improve NUE in rice–wheat cropping systems grown with novel crop establishment methods. Further research using an integrated approach to crop, soil, water and nutrient management at the cropping system level should be adopted to improve the productivity and sustainability of rice–wheat cropping systems in South Asia and China. Long term studies with well managed experiments will provide insights into N dynamics and cycling so that interventions can be formulated for overcoming site specific limitations to increasing NUE in these high input, intensive cropping systems.

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