SARP Research Proceedings

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- ZAU - Zhejiang Agricultural University, Hangzhou, Zhejiang Province

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- IARI-WTC - Indian Agricultural Research Institute, Water Technology Center, New Delhi
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SARP Research Proceedings

Nitrogen economy of irrigated rice: field and simulation studies

Proceedings of the
' International Workshop on Nitrogen Management and Modelling
in Irrigated Rice', held at
the Crop Experiment Station, Rural Development Administration,
Suweon, Korea, 1 - 10 November 1993

H.F.M. ten Berge, M.C.S. Wopereis & J.C. Shin (Editors)

SARP Research Proceedings - April 1994

DLO-Research Institute for Agrobiology and Soil Fertility, Wageningen
Department of Theoretical Production Ecology, Wageningen
International Rice Research Institute, Los Baños

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Nitrogen

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Preface

This volume of the SARP Research Proceedings compiles recent work on rice-nitrogen relations conducted by the various centres participating in the SARP research network. Most of the papers included were presented at the 'International Workshop on Nitrogen Management and Modelling in Irrigated Rice', held 1-10 November 1993 at the Crop Experiment Station, Suweon, Korea.

Rice scientists from 13 sites in six countries, including agronomists, soil scientists, plant and crop physiologists, and plant breeders contributed to these proceedings. They are all involved in SARP's 'Crop and Soil Management' research theme.

The idea to conduct a series of 'Common Experiments' was conceived in 1990 during one of the training workshops on simulation and systems analysis. It was then felt that the applicability of simulation models, both for forecasting and as management tools, was limited because insufficient quantitative insights existed into basic rice-nitrogen relations. Such relations affect nitrogen (N) conversions in soil and floodwater, root growth, the uptake of N by the crop, and its utilization in converting radiation into biomass and, ultimately, grain yield.

Thus, three 'groups' of experiments were succesively proposed by participating researchers. The first group - Common Experiment I - focussed on N uptake in relation to root growth, nitrogen application, and ammonium concentration in the soil solution. The results were presented at a workshop hosted by the Universiti Pertanian Malaysia, May 1991, and have been reported elsewhere. These experiments generated new information about temporal variations of nitrogen uptake and root growth under 'normal' N application strategies, and provided a first basis for assessing fertilizer-N recovery as a function of the time of application. The observations on soil solution ammonium, however, proved afflicted with methodological problems.

Common Experiment II was designed during the above 'Malaysia meeting' to investigate feedbacks between antecedent cumulative crop N uptake and current uptake rate. The experimental setup enabled the determination of fertilizer recovery 'per split dose' applied. The basic layout consisted of four treatments: fertilizer-N is or is not applied at transplanting; and fertilizer-N is or is not applied at the stage of panicle initiation. The resulting extreme N application schemes were not evaluated as alternatives to recommended management practice, but to expose the processes underlying N uptake and utilization.

During the International Rice Research Conference at IRRI in April 1992, a small group convened to propose Experiment III. The purpose this time was to determine maximum and minimum N concentrations in plant tissues, and to determine the N uptake capacity of the crop at different stages under conditions of non-limiting N supply. The experiment included a single - excessive - level of total N input for all treatments, but the number of doses was varied in the different treatments, thereby shifting the date of the first application and sometimes also the latest application.

Experiments II and III were conducted at several locations in India (Orissa, Tamil Nadu), Indonesia (West Java), and The Philippines (Laguna), each with slight variations. Most of the results are presented here, although a number of experiments still remain undocumented. The first eight papers of this volume are reports of these common experiments. There was a certain degree of liberty to tailor each of the trials to suit local conditions (e.g. by choosing the total N input level) and individual interests (extra treatments were often included). Because of these variations, the experimental details are provided in every paper. Tables with basic observations are included as much as possible, in order to fully document the trials. Some of the papers combine two or more experiments.

The next five papers in this proceedings describe other process oriented experiments, some investigating the role of organic or plant residue manures (Budhar et al.; Palaniappan et al.), others focussing on root growth in relation to drainange (Ramasamy et al.) or soil ammonium dynamics (Sismiyati et al.). This group also includes a paper on N uptake and utilization by hybrid rices in China (Qinghua et al.).

The remaining nine papers describe concepts or models, some of them based upon results presented in the first part of this volume, or earlier (Thiyagarajan et al.; Pannangpetch et al.; ten Berge et al.). Some of these contributions apply the information obtained from detailed process oriented work to generate fertilizer management recommendations and yield forecasts. Two contributions not directly related to rice-nitrogen were included since this work was done in the context of the 'Crop and Soil Management' theme, too (Singh; Kalra et al.). Gaunt et al. elaborate on the methodology of soil solution sampling in flooded rice and its above-mentioned problems. The last three short contributions discuss the potential limitations to nitrogen uptake by rice roots and include detailed considerations on rhizosphere and floodwater chemistry. One of these notes (Cassman et al.) proposes an experimental approach to assess the capacity of the root system to absorb nitrogen at different growth stages.

Returning to the issue of applying models to improve input management at the farm level, we feel that now a more solid basis exists to underpin hypothetical crop and soil management strategies. This book provides a rich source of information, analyses and viewpoints which can be applied to improve and site-tailor management in the field. Much of the collected information has to be further analyzed and applied. That will be the task for the remaining 1.5 years in SARP's third project phase. For a start, the workshop reported here concluded last November that the next common experiment (IV) will address computer-based site-specific fertilizer management recommendation in comparison with current recommendations by the extension services. This will be done during 1994 in India, China, Indonesia, and The Philippines. In the state of Tamil Nadu, nine substations of the Tamil Nadu Rice Research Institute (Aduthurai) will include such comparison trials in their experimental work, and their researchers will be trained to use the tools now (early 1994) available.

Acknowledgements

The workshop reported in this document was only possible due to the excellent and unremitting organization by the rice research group at CES, headed by Dr M.H. Lee and Dr Yun Jin Oh, director of the Rice Production Division, and by Ms Susan Telosa at IRRI. The logistics provided by their interactions and energy were crucial to the success of the meeting.

We thank Mrs B. Hulshorst of Tekst2000 for her unflagging assistance to process and correct late arriving manuscripts, thus allowing the completion of these proceedings within five months after the reported workshop.

The editors.

Contents

Growth, yield and uptake of nitrogen by irrigated rice as affected by timing of fertilizer application

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Abstract

A field experiment on N uptake and recovery of irrigated rice was conducted at the Central Rice Research Institute (CRRI) in Cuttack, India, during the dry season of 1992. The uptake and recovery of 100 kg N/ha applied at panicle initiation (PI) stage was studied as a function of prior N status of the crop. The N status of rice at PI was varied by applying either no nitrogen or 100 kg N/ha at 13 days after transplanting (DAT). The N content of all plant organs (i.e. leaves, stems and roots) peaked at 22 DAT, after which it decreased continuously until harvest if no more N was applied. The N content of leaves, stems and roots suddenly increased if 100 kg N/ha was applied at PI (43 DAT). The biomass of leaves, stems and roots increased for all treatments and peaked at flowering stage. The application of 100 kg N/ha at PI without any previous N application resulted in sudden increases in leaf, stem and root biomass in the reproductive phase. These increases were, however, still lower than the corresponding biomass increases resulting from an one time application of 100 kg N/ha at 13 DAT. The weight of panicles in the reproductive phase was higher when 100 kg N/ha was applied at PI. The total N uptake by rice increased from transplanting to maturity. The recovery of 100 kg N/ha applied at 13 DAT or at PI was similar. The grain yield of rice was highest when 100 kg N/ha was applied at PI without prior N application. The relationship between maximum N uptake and dry matter yield was slightly curvilinear. The recovery of 100 kg N/ha applied at PI was around 30%, two days after application. However, at 62 DAT, almost all the N from the second split application at PI stage was recovered by the crop.

Introduction

In most rice soils application of N fertilizer is necessary, especially if nitrogen responsive, modern rice cultivars are grown with improved cultural practices. There are two reasons for not getting expected yield levels after application of fertilizer N to rice. Either the recovery of fertilizer N is poor or the efficiency at which nitrogen, once taken up, is used for grain production is low. To study both fertilizer N recovery and crop nitrogen utilization, a series of experiments were conducted at several locations within the framework of SARP. This paper presents the results of an experiment designed to reveal the effects of early crop N status on recovery of fertilizer N applied at panicle iniation (PI) stage, and on utilization of N by the crop.

Materials and methods

A field experiment was conducted during the dry season of 1992 at the Central Rice Research Institute, Cuttack (20.5^o N, 86.5^{o}E), Orissa, India, to study growth, yield and N uptake by irrigated rice, as affected by N status of the plant. The experimental site is situated in the Mahanadi delta. The soil is of clay loam texture and is classified as a Typic Haplaquept with a pH of 6.1 and a CEC of 15 me/100g. Treatments comprised timing and rate of N fertilizer application (Table 1): 100 kg N/ha was applied at PI (T2), 13 DAT (T3) or at both 13 DAT and PI (T4). A control treatment (no N) was also included (T1). All four treatments were replicated three times in a complete randomized block design. Plot size was 30 m^2. N was broadcasted in the form of urea. P and K were applied basally at a rate of 40 kg/ha and 30 kg/ha respectively. Seedlings of cv. IR36 (21 days old) were transplanted in puddled soil on 28 January 1992. Plant spacing was 20 cm x 10 cm. The seedlings were collected from a nursery sown on 8 January 1992 which received 10 kg N/ha as urea 15 days after sowing. Adequate plant protection measures were taken throughout the crop cycle. Plots remained flooded throughout the experiment.

At 0, 14, 16, 22, 32, 39, 43, 45, 62, 72 and 93 DAT, 10 hills were sampled in each plot and dry weights of leaves, stems (including leaf sheaths), roots, panicles and grains were determined. Samples were, therefore, collected just before and after fertilizer application. Samples for T1 and T2 and samples for T3 and T4 were combined to composite samples up to 43 DAT. The number of tillers in each sample was counted. The N content of all plant organs was determined using the micro-Kjeldahl distillation method. Per plot a 5m^2 harvest area was used to determine final straw and grain yield.

Table 1. Overview of timing and rate of fertilizer N application for the various treatments in the field experiment. Cuttack, dry season, 1992.

Treatment	N applied at 13 DAT (kg/ha)	N applied at PI (kg/ha)	Total (kg/ha)
T1	0	0	0
T2	0	100	100
T3	100	0	100
T4	100	100	200

Results and discussion

Panicle initiation was reached at 43 DAT for all treatments. Flowering (defined as the moment when 50% of the hills have at least one flowering panicle) occurred at 76, 74, 77 and 74 DAT for T1, T2, T3 and T4 respectively. Topdressing of N at PI (T2, T4) resulted, therefore, in earlier flowering. All plots were harvested at 108 DAT.

Number of tillers per m^2

Application of N resulted in a larger number of tillers per m^2 than was observed for the zero-N treatment (Figure 1). The highest number of tillers per m^2 at any stage was observed for T4. If 100 kg N/ha was applied at PI to a crop with a low N status (T2), an increase in tiller number per m^2 was observed up to 62 DAT, and a decrease from 62 DAT up to harvest. Tiller number at harvest was higher for T2 than for T3.

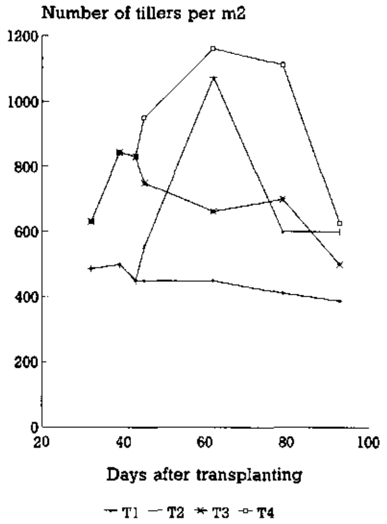

Figure 1. Number of tillers per m^2 at different growth stages of cv IR36. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Dry weight of plant organs

Application of N resulted in an increase in biomass of leaves, stems and roots. (Tables 2, 3 and 4). The highest leaf weight at any growth stage was observed for T4. T2 leaf weights increased after N application at PI but remained lower than T3 (Table 2). In all treatments, stem weight increased until flowering and decreased afterwards (Table 3). In contrast to leaf weight, stem weights were highest for T3, at any stage of the experiment. T2 (low N status at PI) stem weight increased after N application, but did not reach the stem weight observed for T3. The fact that T4 stem weights were lower than T3 stem weights might be attributed to reduced accumulation of stem reserves under high N conditions (Yoshida, 1981).

Table 2. Dry weight of green leaves (kg/ha) of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Treatment	Days after transplanting										
	0	14	16	22	32	39	43	45	62	79	93
T1	4.5	33.3	33.4	93.6	362	525	581	675	1400	1588	1125
T2	4.5	33.3	33.4	93.6	362	525	581	825	1950	2200	2163
T3	4.5	35.7	45.4	141.5	550	944	1269	1338	2088	2313	2513
T4	4.5	35.7	45.4	141.5	550	944	1269	1350	3525	3700	3025

Table 3. Dry weight of stems (kg/ha) of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Treatment	Days after transplanting										
	0	14	16	22	32	39	43	45	62	79	93
T1	4.6	26.6	30.7	93.8	406	806	894	1050	3075	4750	3188
T2	4.6	26.6	30.7	93.8	406	806	894	1163	3188	5625	4412
T3	4.6	31.4	41.1	120.2	643	1131	1663	1750	4900	6563	5300
T4	4.6	31.4	41.1	120.2	643	1131	1663	1688	4750	6025	4963

Table 4. Dry weight of roots (kg/ha) of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Treatment	Days after transplanting										
	0	14	16	22	32	39	43	45	62	79	93
T1	2.5	10.2	12.4	34.2	193	481	556	638	1550	1287	575
T2	2.5	10.2	12.4	34.2	193	481	556	638	1087	1225	862
T3	2.5	13.8	11.8	47.0	256	625	794	1012	1475	2050	1650
T4	2.5	13.8	11.8	47.0	256	625	794	812	1100	1637	1100

The weight of the roots (Table 4) continued to increase until flowering after which it decreased. Highest root weight was observed in T3 at all stages of crop growth.

The weight of panicles at 79 DAT was lowest in Tl and T3 (Table 5), which can be explained by the delay in flowering date. Panicle weights of T3 increased more rapidly from 79 DAT to harvest than of T2. De Datta (1978) observed that N uptake by the plant from tillering to panicle initiation tends to increase the number of tillers and panicles. N absorbed during panicle development (from panicle initiation to flowering) increases the number of filled spikelets per panicle. Nitrogen uptake after flowering tends to increase the 1000 grain weight. The present experiment confirms these observations. The number of panicles in T2 (Table 5) was lower than in T3, but the weight of panicles (i.e. the combined result of spikelet number per panicle and 1000 grain weight) was higher.

It is interesting to compare the time course of dry matter accumulation for T2 and T3 (Figure 2). T3 dry matter production increased gradually from transplanting to harvest, whereas T2 total dry matter increased suddenly after PI due to the fertilizer application, thereby reducing the initial large difference between these two treatments.

Table 5. Dry weight of panicles (kg/ha) and number of panicles per m^2 of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Treatment	Number of panicles m^{-2}		Weight of panicles (kg/ha)	
	Days after transplanting		Days after transplanting	
	79	93	79	93
Tl	325	375	2138	4288
T2	375	463	2900	6912
T3	388	488	1912	6550
T4	513	538	2863	8438

Total N uptake

High levels of N application resulted in a higher crop N uptake (Figure 3). When 100 kg N/ha was applied at PI to a crop of low N status (T2), total N uptake increased rapidly upto 181 kg/ha at harvest. The T2 N-uptake surpassed the T3 N-uptake at 62 DAT. Tanaka et al. (1959) found that at high N rates (i.e. 120 kg N/ha), nitrogen absorbed by the crop during the vegetative stage is stored for use at later growth stages. Temperature has a great effect on the mineralization and absorption of soil nitrogen. Yanagisawa and Takahashi (1964) reported that rice on the highly productive soils in the cooler parts of Japan derived 60-80% of total N uptake from the soil during the later growth stages. In the present experiment, absorption of nitrogen was still possible after flowering presumably because the temperature was relatively high.

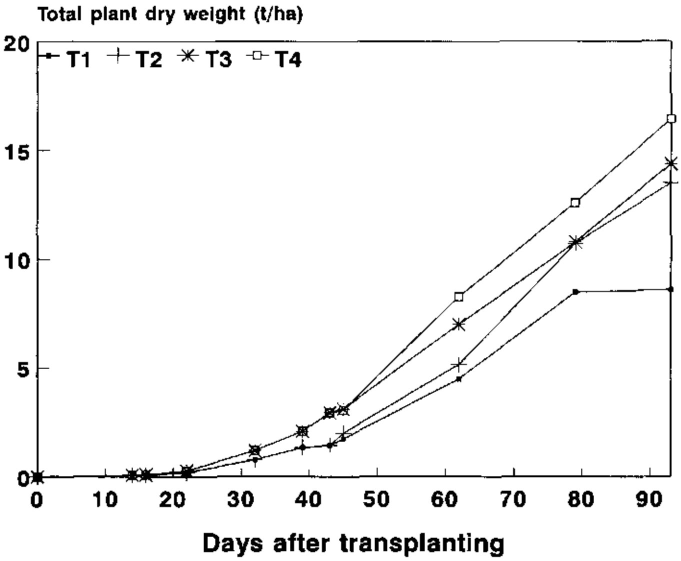

Figure 2. Total above ground dry matter (kg/ha) of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

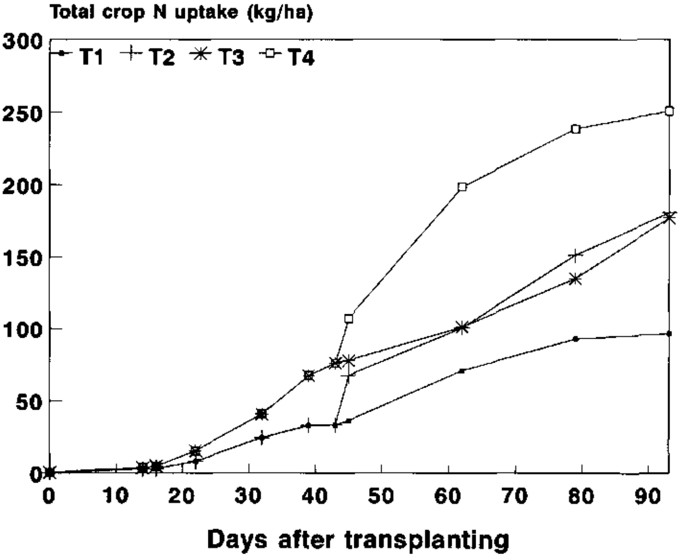

Figure 3. Total N uptake (kg/ha) of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Table 6. Grain and straw yield (t/ha) and grain : straw ratio at harvest of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Treatment	Grain	Straw	Total	Grain:Straw
T1	5.2	5.0	10.2	1.04
T2	7.2	6.0	13.8	1.09
T3	6.0	6.8	12.8	0.88
T4	6.8	8.2	17.5	0.83

Grain and straw yields

Rice grain and straw yields (Table 6) were lowest in the control (no nitrogen) treatment. Highest grain yields were observed for T2, whereas highest straw yields were found in case of T4. Straw yields of T2 and T3 were quite similar, but the difference in grain yield was substantial. The grain:straw ratio was highest for T2 followed by T1. Application of 200 kg N/ha lowered the grain:straw ratio compared to all other treatments.

N content of stems and leaves

The N content of leaves and stems reached its maximum at 22 DAT (Tables 7 and 8) and decreased continuously until harvest for T1 and T3. Topdressing at PI (T2 and T4) caused a sudden increase in N content. Maximum leaf N content was 7.0%. T4 showed the highest stem and leaf N contents at all stages of crop growth. Tanaka (1964) also observed higher leaf N contents at early growth stages of rice. Yanagisawa et al. (1967) found that nitrogen applied at PI or at flowering reduced the rate of senesence of the lower leaves.

The straw N content at harvest was similar for T2, T3 and T4 (1.2%) and higher than T1 (0.8%).

Table 7. N content (%) of green leaves of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Treatment	Days after transplanting										
	0	14	16	22	32	39	43	45	62	79	93
T1	3.4	5.1	5.5	5.5	4.0	3.4	2.9	2.8	2.2	1.5	1.5
T2	3.4	5.1	5.5	5.5	4.0	3.4	2.9	3.9	2.8	1.7	1.7
T3	3.4	5.8	5.9	7.0	4.4	4.0	3.3	3.3	2.2	1.6	1.5
T4	3.4	5.8	5.9	7.0	4.4	4.0	3.3	3.9	3.1	2.3	1.9

Table 8. N content (%) of stems of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Treatment	Days after transplanting										
	0	14	16	22	32	39	43	45	62	79	93
T1	2.1	2.3	2.9	2.6	1.7	1.2	1.1	1.1	0.9	0.7	0.7
T2	2.1	2.3	2.9	2.6	1.7	1.2	1.1	2.1	1.2	1.0	0.7
T3	2.1	3.1	3.4	3.6	2.0	1.8	1.5	1.3	1.0	0.8	0.7
T4	2.1	3.1	3.4	3.6	2.0	1.8	1.5	2.6	1.6	1.2	1.0

Table 9. N content (%) of roots of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Treatment	Days after transplanting										
	0	14	16	22	32	39	43	45	62	79	93
T1	2.0	2.0	1.8	1.5	1.4	1.2	1.0	0.9	0.8	1.0	0.9
T2	2.0	2.0	1.8	1.5	1.4	1.2	1.0	1.3	0.9	1.1	1.0
T3	2.0	2.5	2.5	2.2	1.5	1.5	1.2	1.1	0.9	1.0	1.0
T4	2.0	2.5	2.5	2.2	1.5	1.5	1.2	1.3	1.2	1.3	1.0

N content of roots

Early application of N resulted in a significant increase in root N content (Table 9). The root N content was high at 14 DAT and decreased continuously until 62 DAT in case of T1 and T3. T2 and T4 root N contents peaked at 45 DAT due to the fertilizer application at PI. Highest root N contents at any time during the experiment were observed for T4.

N content of panicles and grains

Highest panicle N contents (Table 10) were found in T2 and T4 where flowering occurred earlier than in the other two treatments. High N content during the middle of the crop cycle ensures an adequate number of spikelets to achieve high yield but may cause lodging and poor filling of grains due to shading as a result of vigorous vegetative growth (Murayama, 1979). A high N content is, however, required during grain filling if carbohydrate supply to grains is to be maintained by photosynthesis. The grain N content at harvest was 1.4% for T4 and 1.2% for T1, T2 and T3.

Table 10. N content (%) of panicles of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Treatment	Days after transplanting	
	79	93
T1	1.0	1.2
T2	1.5	1.5
T3	1.2	1.3
T4	2.0	1.6

Total N-uptake of plant organs

The proportion of total N-uptake by each of the plant organs is shown in Figure 4. For all treatments the proportion of total absorbed N by the leaves was highest among the plant organs upto 45 DAT. In case of T4, this was also true at 62 DAT. The proportion of absorbed N by the roots was highest during the period from 39 DAT to 45 DAT (PI stage). The amount of N allocated to the stems was highest for T2 from 62 DAT onwards, ultimately leading to the highest yield.

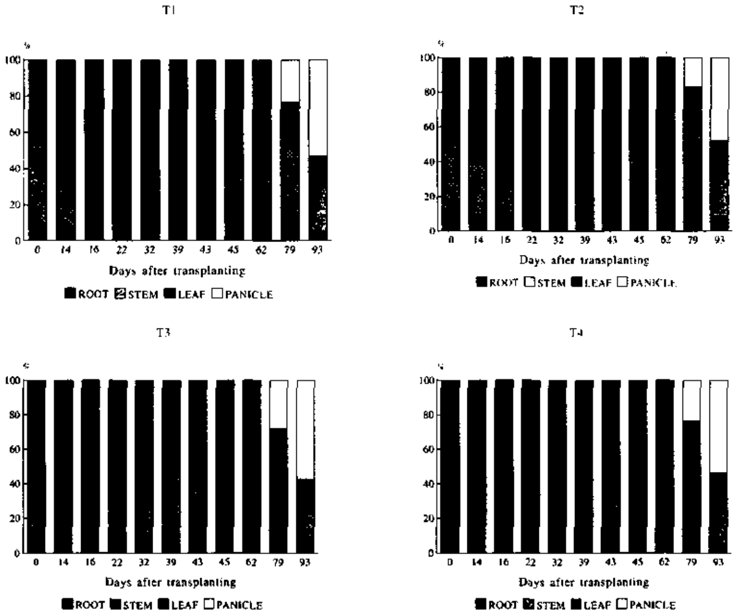

Figure 4. The proportion of absorbed N in different plant organs of cv IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Leaf:stem and root:shoot ratios

The leaf:stem ratio (Figure 5) generally increased after N application. The highest leaf:stem ratio was found for T4 throughout the experiment. The root:shoot ratio (Figure 6) decreased upon N application. T4 maintained the lowest root: shoot ratio at all stages of crop growth. Application of 100 kg N/ha to a crop of low N status at PI reduced the root:shoot ratio. This ratio was comparable to the root:shoot ratio in treatment T3 during 45-62 DAT. Between 79-93 DAT the root:shoot ratio in treatment T2 was lower than in treatment T3.

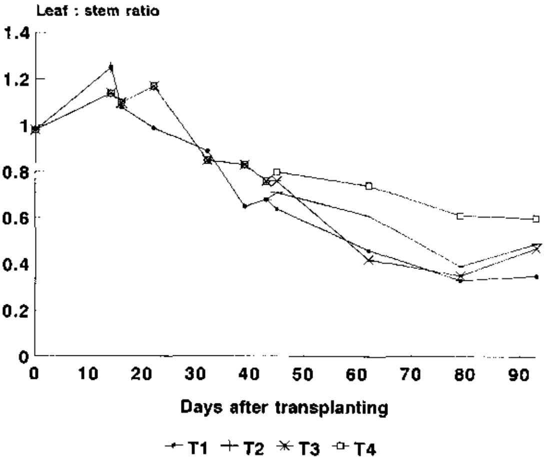

Figure 5. Leaf:stem ratios of IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

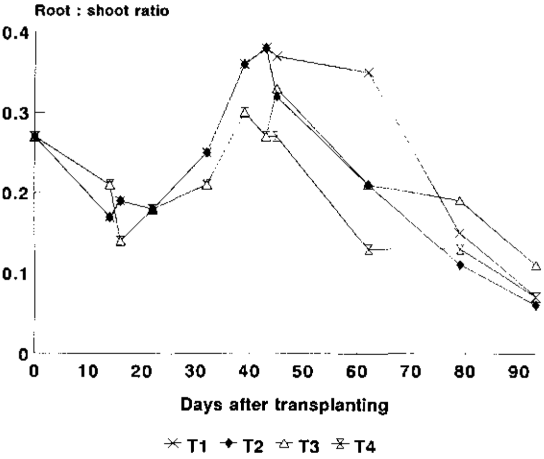

Figure 6. Root:shoot ratios of IR36 in the field experiment. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Recovery of N from the second fertilizer application

The recovery of the 100 kg N/ha applied at PI by the rice crop, and its dependence on prior crop N status was investigated (Figure 7). The total N uptake of the crop from PI to harvest was compared for the various treatments. To account for the differences in N status at PI, T2 was compared with T1 and T4 with T3. The difference in N uptake, divided by the 100 kg N/ha that was applied at PI is considered as the apparent recovery of N applied at PI. The very high rate at which N is absorbed directly after application is remarkable (apparent N recovery is about 0.3 at 45 DAT). At 62 and 79 DAT almost all N applied at PI was recovered by the crop with high N status at PI (T4). At low N status at PI (T2) the recovery of PI applied N was lower and continued to increase slowly from 0.31 to 0.84 (kg N recovered) / (kg N applied) during the 45 - 93 DAT period. At 93 DAT, total N uptake of T2 and T3 was similar (Figure 3), which implies that the recovery of the N applied at PI in T2 was comparable to the recovery in T3 of the early applied N. The efficiency of N uptake from fertilizer at different times of application has been determined by tracer techniques. Yanagisawa et al. (1967) found that 55% of nitrogen applied before heading was taken up by the plant. At flowering recovery was 49%, at tillering 34%, and at transplanting as a basal dressing 7%.

Studies in California showed that 45% of tracer 15N was absorbed when nitrogen was topdressed at the booting stage (Patnaik and Broadent, 1967). In this experiment, recovery percentages were much higher from 62 DAT to 79 DAT, probably due to absorption of soil N together with fertilizer N applied at PI (Broadbent and Reyes, 1971). The application of fertilizer N might have stimulated the release of soil N during the reproductive phase as was also observed by Koyama et al. (1973) and Westerman and Kurz (1973).

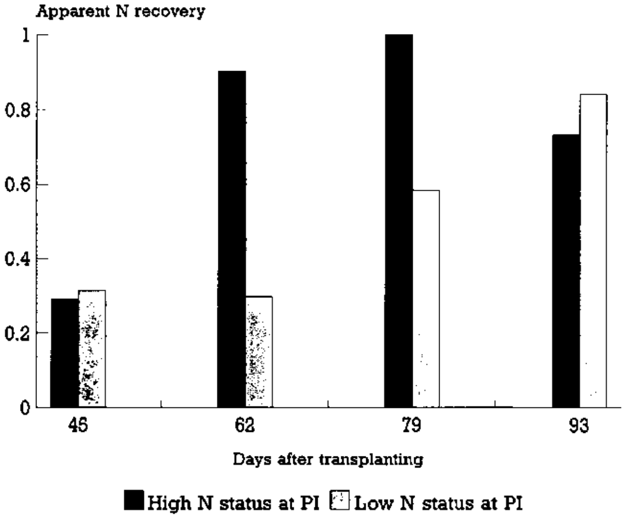

Figure 7. Apparent recovery (kg uptake / kg applied) by cv IR36 of N applied at PI. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Relation between N in the crop and total dry matter and yield of rice

The relationship between maximum crop N uptake and maximum dry matter and yield of rice was examined (Figure 8). The relationship between maximum N uptake and dry matter production is slightly curvilinear. However, no such relationship exists between maximum N uptake by the crop and grain yield. Whereas dry matter production appeared to be determined by the amount of applied N and less by timing of application, grain yield responded strongly to both timing and application level.

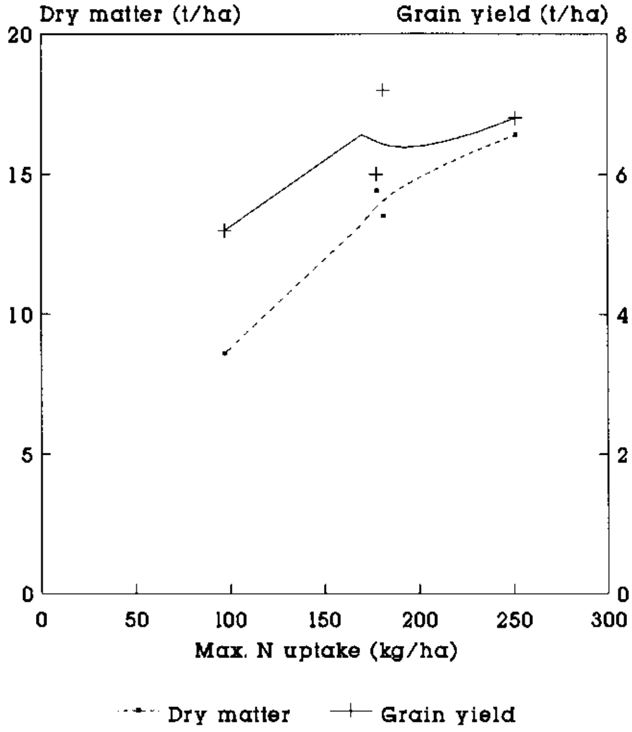

Figure 8. The relationship between crop N uptake and maximum dry matter and grain yield of cv IR36. Treatment codes are explained in Table 1. Cuttack, dry season, 1992.

Conclusions

Application of N at PI increased dry weights of leaves, stems, and panicles, and also their N content and total N uptake in a crop with either initial low or high N status.

Grain yield responded strongly to the amount and timing of N application. The apparent recovery of applied N at PI was higher for a crop with high initial N status than for a crop with low initial N status. There was a close relationship between maximum crop N uptake and total dry matter yield of rice.

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The effect of time of nitrogen application on growth and performance of rice - a process study

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Abstract

Two field experiments were conducted at the Central Rice Research Institute (CRRI), Cuttack, Orissa, India, one during the wet season of 1991 (Experiment I) and one in the dry season of 1993 (Experiment II). Experiment I was designed to study the nitrogen (N) uptake from 100 kg urea-N/ha applied at panicle initiation (PI) by rice cultivar IR36, as a function of prior crop N status. Two levels of crop N status at PI were established by applying either no N or 100 kg N/ha at 10 days after transplanting. In Experiment II, 200 kg N/ha was applied in different splits coinciding with various growth stages. The maximum number of urea applications was 7, i.e. at transplanting, seedling establishment, active tillering, maximum tillering, PI, in between PI and flowering, and at flowering. Observations on biomass and nitrogen content of roots, stems, leaves, panicles and yield and yield attributes were recorded.

In Experiment I, application of 100 kg N/ha at PI increased the grain yield through an increase in the number of productive tillers, filled grains and the 1000-grain weight. The magnitude of increase was larger for a crop with low initial N status than for a crop with high initial N status. The recovery percentage of total applied N as well as of the second N split was larger for a crop with a lower initial N status.

In Experiment II, highest yields (around 7.5 t/ha) were obtained when N was applied in 5 or more splits either skipping a basal application or applications in between PI and flowering and at flowering. Delay in N application beyond active tillering stage reduced grain yield by reducing the number of panicles. Similarly, the omission of N application after the active tillering stage reduced grain yield by reducing harvest index and increasing the number and percentage of unfilled grains.

In both experiments the percentage of unfilled grains was relatively high (i.e. 30% in Experiment I and 20-25% in Experiment II).

Introduction

Nitrogen (N) is an important growth limiting factor for rice. Recovery of fertilizer N applied at different growth stages may vary widely. It is therefore important to develop a good understanding of the processes of nitrogen transformations in soil and plant. Much work on N in rice has focussed on loss processes in relation to flood water and soil chemistry and biology (De Datta and Patric, 1986). Detailed physico-chemical models have recently become available (Rachpal Singh and Kirk, 1993) which serve as a basis for understanding the fate of mineral N in the soil-water system. Also, the utilization of N by the crop, once it is absorbed, and its effects on dry matter production are now largely understood (Yoshida, 1981., Kropff et al., 1993). Gaps still exist in our understanding of certain aspects, e.g. dry matter partitioning and sink formation as a function of N uptake, and N uptake capacity of the rice crop as a function of current N status of the crop. An understanding of such topics is essential to extrapolate quantitative results from agronomic research to other environments, to develop new nutrient management strategies with reduced losses to the atmosphere and ground water and to provide guidance to breeding programmes. The present study addresses two questions: (1) how does the N status of the crop, at a given development stage, determine the capacity of the crop to take up N from the soil? (2) how does growth and grain yield of rice respond to the application of a similar amount of N given at different growth stages? Two experiments conducted along the lines of a common design proposed within the SARP research framework (see the introduction to this volume) are reported here.

Materials en methods

Experiment I

This experiment was conducted during the wet season of 1991 at the Central Rice Research Institute (CRRI), Cuttack, India (20.5°N, 86.0°E) to study the growth, yield, N uptake and recovery from nitrogen application at panicle initiation (PI) in relation to prior N status of the crop. The soil was of clay loam texture (Mahanadi delta sediment), classified as a Typic Haplaquept (pH = 6.1, CEC = 15 me/100 g and N = 0.07%). Different levels of pre-PI crop nitrogen status were established by applying either no nitrogen or 100 kg N/ha at 10 days after transplanting (DAT). At PI again either no nitrogen or 100 kg N/ha was applied. The treatments and other experimental details are given in Table 1. The experiment was conducted in a complete randomized block design with 4 replicates per treatment. Plot size was 25 m^2. Twenty five days old seedlings of a medium duration rice variety IR36 were transplanted in puddled soil on 11 September, 1991 with a plant spacing of 15cm x 15cm. The seedlings were collected from a nursery sown on 17 August, 1991 which received 10 kg N/ha as urea 15 days after sowing. Adequate plant protection measures were taken throughout the growth period of the crop. P and K fertilizer were applied basally at a rate of 50 kg/ha each.

Table 1. N-fertilizer treatments in Experiment I (Cuttack, wet season, 1991).

Treatment code	Nitrogen application (kg/ha)		Total
	AT 10 DAT	AT PI	
T1	0	0	0
T2	0	100	100
T3	100	0	100
T4	100	100	200

Experimental details :

Variety	: IR36	
Plant spacing	: 15 cm x 15 cm	
Dates of		
Seeding	: 17.08.1991	
Transplanting	: 11.09.1991	
Maximum tillering	: 11.10.1991	30 DAT
Panicle initiation	: 23.10.1991	42 DAT
Flowering	: 11.11.1991 (T1 & T3)	62 DAT
	: 15.11.1991 (T2 & T4)	66 DAT
Harvesting	: 16.12.1991	97 DAT
Fertiliser Application :		
1st Split	: 21.09.1991	10 DAT
2nd Split	: 23.10.1991	42 DAT
Sampling:		
1st Sample	: 20.09.1991	10 DAT
2nd Sample	: 01.10.1991	21 DAT
3rd Sample	: 21.10.1991	41 DAT
4th Sample	: 05.11.1991	56 DAT
5th Sample	: 15.11.1991	66 DAT
6th Sample	: 16.12.1991	97 DAT

DAT = days after transplanting PI = panicle initiation

Eight hills were sampled to determine dry weight of leaves, stem, roots, panicle and grains at 0, 10, 21, 41, 56, 66 and 97 DAT. The crop was harvested on 16 December, 1991 (harvest area = 12 m^2 per plot). A yield component analysis was conducted on 8 hills per plot. For each treatment a harvest index was calculated as grain weight (14% moisture content) divided by total crop dry mass. The ground plant samples and grain samples were analysed for N using the micro-Kjeldahl distillation method.

Experiment II

This experiment was conducted during the dry season of 1993, again at the CRRI experimental farm. Seedlings of rice cvar IR36 (35 days old) were transplanted in puddled soil on 28 January, 1993 at a plant spacing of 15 cm x 15 cm. P and K were applied basally at a rate of 50 kg/ha. Nitrogen (200 kg/ha) was applied as urea in different splits coinciding with various growth stages of the crop (Table 2). Flowering was defined here as the stage when 90% of the hills had at least one flowering panicle. A control (no nitrogen) treatment was included. A standing water depth of approximately 5 cm was continuously maintained throughout the crop growth period. The experiment was laid out in a randomized block design with 3 replications. Plot size was 15 m^2. Adequate plant protection measures were taken throughout the growth period of the crop. Eight hills were sampled to determine dry weights of leaves, stem, roots, panicle and grains at 0, 39, 48, 62, 69 and 92 DAT. Yield (harvest area: 12 m^2 per plot) and yield attributes (from 8 hills per plot) were recorded at harvest. For each treatment the harvest index was calculated as described for Experiment I.

Results and discussion

Experiment I

Dry Weight of Plant Organs

Dry weights of leaves, stems, roots and panicles are presented in Table 3. Total leaf and stem dry weights reached maximum values at flowering stage and thereafter decreased. Highest leaf and stem weight was recorded at all stages of crop growth in case of Treatment T4 where 200 kg N/ha was applied in two equal splits. At initial low N status of the crop (T2), the leaf and stem weights were low initially but increased steeply at 56 and 66 DAT due to application of N at PI. The increase in leaf weight in these treatments was more pronounced than the increase in stem weight. Application of N resulted in greater root production in all treatments compared to the control. Root mass continued to increase until flowering (with a temporary decrease at 56 DAT) after which it declined. The weight of panicles increased as crop growth progressed and reached its maximum at harvest, i.e. at 97 DAT. Delay in flowering was noticed in Treatments T2 and T4 which resulted in low panicle weight at 56 and 66 DAT. However, at harvest the panicle weight was highest in T4. The panicle weight of T2 increased significantly after flowering as compared to T3, such that the initial difference between these treatments narrowed down.

Table 2. N-fertilizer treatments in Experiment II (Cuttack, dry season, 1993).

Treatment	TR	SE 10 DAT	AT 21 DAT	MT 33 DAT	PI 46 DAT	PI-F 56 DAT	F 67 DAT	Total
T1	0	0	0	0	0	0	0	0
T2	0	0	0	0	66.6	66.6	66.8	200
T3	0	0	0	50	50	50	50	200
T4	0	0	40	40	40	40	40	200
T5	0	33.3	33.3	33.3	33.3	33.3	33.5	200
T6	28.5	28.5	28.5	28.5	28.5	28.5	29	200
T7	33.3	33.3	33.3	33.3	33.3	33.5	0	200
T8	40	40	40	40	40	0	0	200
T9	50	50	50	50	0	0	0	200
T10	66.6	66.6	66.6	0	0	0	0	200
T11	100	100	0	0	0	0	0	200

Experimental details:				
Variety	:	IR36		
Plant spacing	:	15 cm x 15 cm		
Dates of				
Seeding	:	25.12.1992		
Transplanting	:	28.01.1993		
Maximum tillering	:	03.03.1993		33 DAT
Panicle initiation	:	15.03.1993		46 DAT
Flowering	:	31.03.1993	(T2 to T6)	62 DAT
		05.04.1993	(T1 & T7 to T11)	67 DAT
Harvesting	:	30.04.1993		92 DAT
Fertilizer application:				
1st Split	:	28.01.1993		0 DAT
2nd Split	:	07.02.1993		10 DAT
3rd Split	:	18.02.1993		21 DAT
4th Split	:	03.03.1993		33 DAT
5th Split	:	15.03.1993		46 DAT
6th Split	:	25.03.1993		56 DAT
7th Split	:	05.04.1993		67 DAT
Sampling:				
1st Sample	:	15.02.1993		18 DAT
2nd Sample	:	08.03.1993		39 DAT
3rd Sample	:	17.03.1993		48 DAT
4th Sample	:	31.03.1993		62 DAT
5th Sample	:	07.04.1993		69 DAT
6th Sample	:	30.04.1993		92 DAT

TR = transplanting,
AT = active tillering
PI = panicle initiation
F = flowering
SE = seedling establishment
MT = maximum tillering
PI-F = in between PI and flowering
DAT = days after transplanting.

Total dry matter production gradually increased with crop age and reached its maximum at harvest for all treatments. The Treatment pairs T1-T2 and T3-T4 produced almost similar dry mass until PI. Thereafter Treatments T2 and T4, which received 100 kg N/ha at panicle initiation, produced more dry matter than T1 and T3. The application of 100 kg N/ha at PI to the crop having low initial N status (T2) resulted in larger increase in dry matter production than for the crop having higher initial N status (T4).

Leaf:Stem Ratio

Leaf:Stem ratios are presented in Figure 1. The leaf:stem ratio was found to be unaffected by the initial higher crop N status at PI, after which high crop N produced higher leaf:stem ratio. T2 maintained the largest leaf:stem ratio at 56 and 66 DAT. At harvest the leaf:stem ratios of T2 and T4 were almost identical.

Total dry matter production gradually increased with crop age and reached its maximum at harvest for all treatments. The Treatment pairs T1-T2 and T3-T4 produced almost similar dry mass until PI. Thereafter Treatments T2 and T4 which received 100 kg N/ha at panicle initiation produced more dry matter than T1 and T3. The application of 100 kg N/ha at PI to the crop having low initial N status (T2) resulted in larger increase in dry matter production than for the crop having higher initial N status (T4).

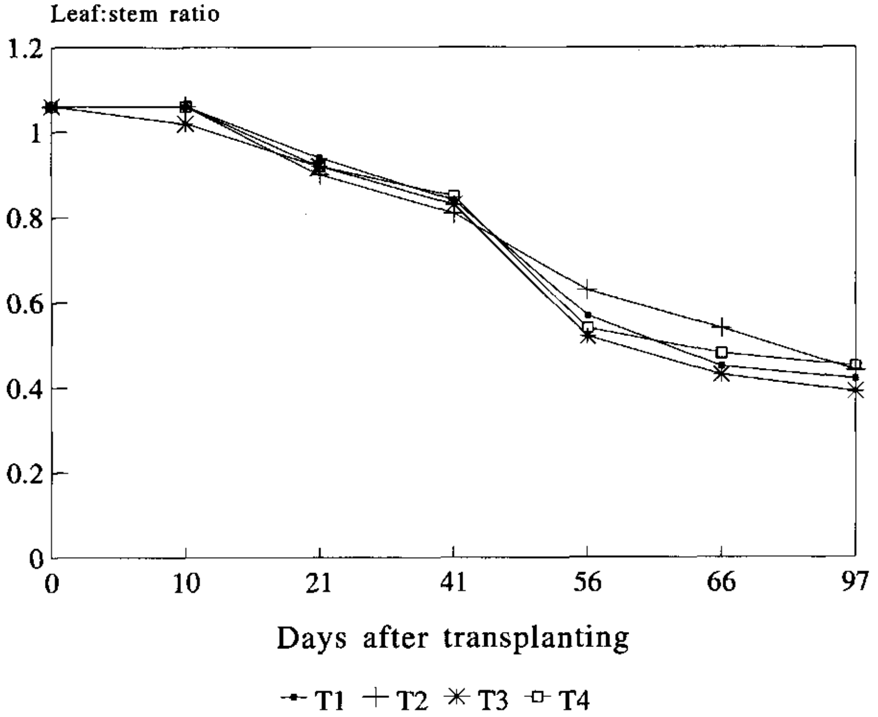

Figure 1. Leaf:stem ratio at different days after transplanting for rice cvar IR36 in Experiment I (Cuttack, wet season 1991).

Table 3. Dry weight (kg/ha) of roots, stems, leaves and storage organs of rice cvar IR36 in Experiment I (Cuttack, wet season, 1991) at different days after transplanting (DAT). Treatment codes are explained in Table 1.

Treatment	0 DAT	10 DAT	21 DAT	41 DAT	56 DAT	66 DAT	97 DAT
	Biomass of leaves (kg/ha)						
T1	34	51	152	981	1161	1160	822
T2	34	51	157	966	1295	1437	961
T3	34	52	221	1133	1363	1397	1008
T4	34	52	215	1141	1440	1575	1185
	Biomass of stems (kg/ha)						
T1	32	48	161	1212	2044	2568	1968
T2	32	48	175	1189	2065	2680	2198
T3	32	51	240	1358	2618	3216	2605
T4	32	49	233	1350	2675	3285	2615
	Biomass of roots (kg/ha)						
T1	23	50	126	572	476	543	414
T2	23	46	128	577	504	602	465
T3	23	53	172	607	526	702	591
T4	23	53	165	608	557	705	581
	Biomass of panicles + grains (kg/ha)						
T1	-	-	-	-	305	1779	3621
T2	-	-	-	-	201	1771	4702
T3	-	-	-	-	241	1948	4819
T4	-	-	-	-	233	1766	5213
	Total crop biomass (kg/ha)						
T1	89	149	439	2765	3986	6050	6825
T2	89	145	460	2732	4065	6490	8326
T3	89	156	633	3098	4748	7263	9023
T4	89	154	613	3099	4905	7331	9594

Nitrogen in Plant Organs

The nitrogen contents of leaves, stems, roots, and panicles are presented in Table 4. The nitrogen content of leaves and stem attained their maximum values at 21 DAT. For roots this occurred at 10 DAT (T1, T2) and 21 DAT (T3, T4). A peak in N content was observed in T2 and T4 at 56 DAT due to nitrogen application at PI. The nitrogen content of panicle and grains was highest for the T2 and T4 Treatments throughout the reproductive phase.

Table 4. N content (%) of leaves, stems, roots and storage organs of rice cvar IR36 in Experiment I (Cuttack, wet season, 1991) at different days after transplanting (DAT). Treatment codes are explained in Table 1.

Treatment	0 DAT	10 DAT	21 DAT	41 DAT	56 DAT	66 DAT	97 DAT
	Nitrogen content (%) of leaves						
T1	3.42	5.12	5.51	2.93	2.41	2.20	1.30
T2	3.42	5.12	5.51	2.93	3.65	2.83	1.63
T3	3.42	5.12	7.00	3.35	3.04	2.35	1.37
T4	3.42	5.12	7.00	3.35	3.75	2.89	1.68
	Nitrogen content (%) of stems						
T1	2.14	2.33	2.65	1.13	1.01	0.91	0.71
T2	2.14	2.33	2.65	1.13	2.05	1.33	0.85
T3	2.14	2.33	3.63	1.50	1.26	1.05	0.79
T4	2.14	2.33	3.63	1.50	2.06	1.41	0.93
	Nitrogen content (%) of roots						
T1	2.01	2.05	1.56	1.01	0.90	0.88	0.74
T2	2.01	2.05	1.56	1.01	1.31	1.02	1.00
T3	2.01	2.05	2.23	1.22	1.13	0.95	0.78
T4	2.01	2.05	2.23	1.22	1.35	1.11	1.00
	Nitrogen content (%) of panicles + grains						
T1	-	-	-	-	1.20	1.15	1.05
T2	-	-	-	-	1.65	1.51	1.35
T3	-	-	-	-	1.39	1.33	1.24
T4	-	-	-	-	1.70	1.61	1.43

The total amount of leaf, stem and root N continued to increase until 56 DAT after which a decrease was observed. Between 46 and 56 DAT the magnitude of increase in total N content of stem and leaf was larger in T2 and T4. In general, the amount of root N continued to increase until flowering. At all growth stages higher N application resulted in a larger amount of root N. Application of 100 kg N/ha at PI to a crop having a low initial N status (T2) resulted in a larger increase in root N content at 56 DAT. The amount of N in panicle and grain gradually increased and reached its maximum at harvest.

Total N uptake and recovery are presented in Figure 2 and Table 5, respectively. In general the total N uptake gradually increased from planting to harvest, with a slight reduction at harvest. However, the reduction was more in Treatment T1 where the crop received no fertilizer-N. Higher levels of N resulted in higher N uptake. From 41 DAT to 56 DAT, the total N uptake almost doubled in T4 and more than doubled in T2 due to the second application of N. The recovery of applied N was highest in T2. The recovery from the second split was higher for the crop having low initial N status at PI (T2) than for the crop having high initial N status at PI (T4).

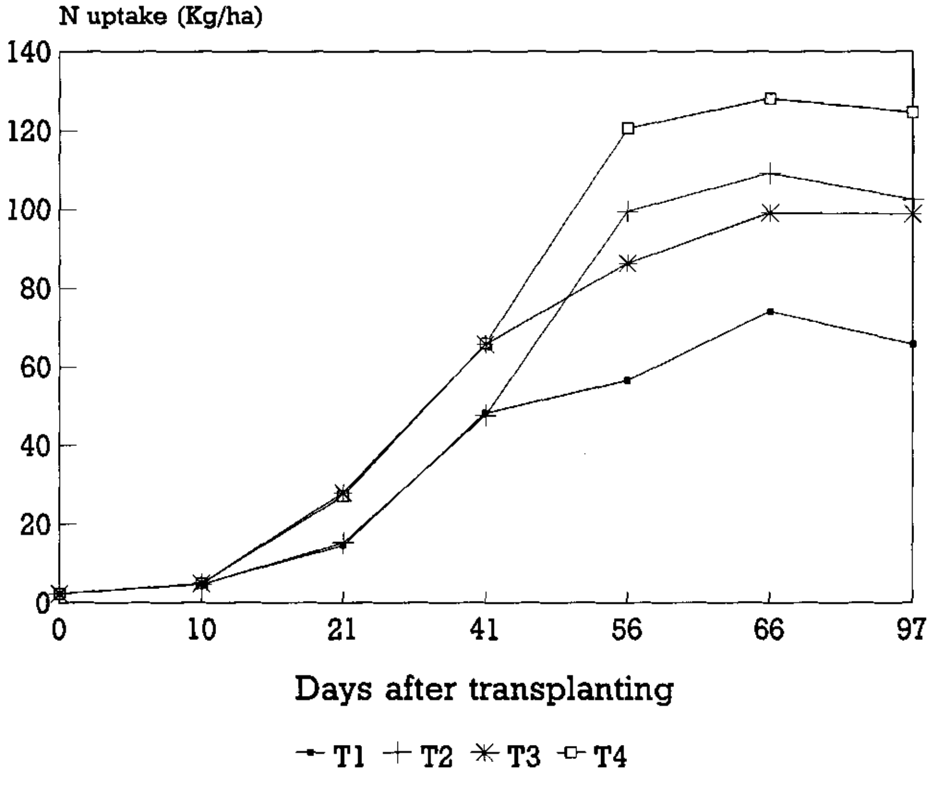

Figure 2. Total N uptake at different days after transplanting for rice cvar IR36 in Experiment I (Cuttack, wet season 1991).

Table 5. Total N uptake and recovery by rice cvar IR36 in Experiment I (Cuttack, wet season, 1991). Treatment codes are explained in Table 1.

Treatment	Total N Uptake (kg ha^{-1})	Recovery from applied N (%)	Recovery from 2nd split (%)
T1	65.7	-	-
T2	102.5	36.7	36.7
T3	98.8	33.0	-
T4	124.6	29.4	25.8

The maximum amount of N in the crop (N_{max}, kg/ha) was observed between PI and flowering in all the treatments except T1 where N_{max} was found at flowering. The grain yield increased with increasing N_{max} (Table 6).

N uptake rates are presented in Figure 3. Peaks at 56 DAT for T2 and T4 and at 21 DAT for T3 and T4 are due to nitrogen application at PI and 10 DAT respectively. However, in T1 the uptake peaks were observed around PI and flowering.

Table 6. Yield and yield components of rice cvar IR36 as affected by timing of nitrogen application in Experiment I (Cuttack, wet season, 1991). Treatment codes are explained in Table 1.

Code	N_{max} kg/ha	Grain yield kg/ha	HI	PAN No m^{-2}	F-GR No m^{-2}	UNF-GR No m^{-2}	UNF-GR %	1000 grain weight g
T1	74.1	3055	0.45	390	14918	7118	32	21.4
T2	109.2	4470	0.54	424	18020	6466	26	22.9
T3	99.2	3870	0.43	440	17600	8800	33	21.4
T4	128.1	4860	0.51	462	20328	8662	30	23.1

HI = harvest index
F-GR = filled grains
N_{max} = maximum amount of N in the crop
PAN = panicles
UNF-GR = unfilled grains
No m^{-2} = number per m^2.

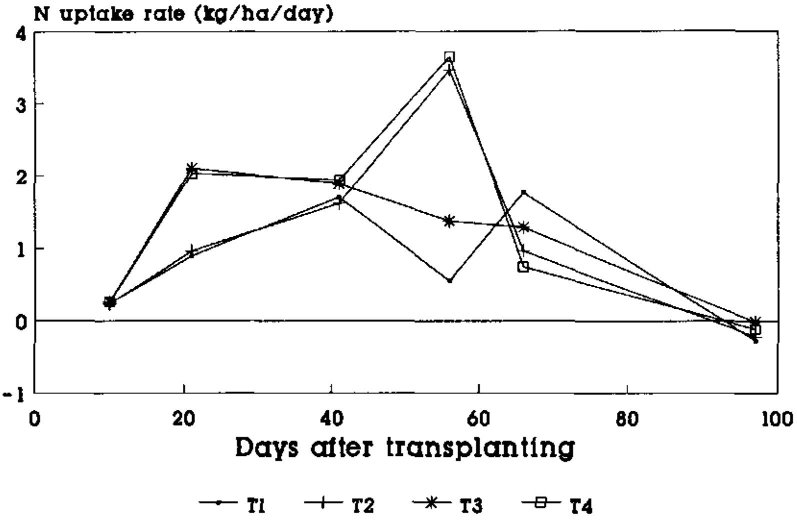

Figure 3. N uptake rate at different days after transplanting for rice cvar IR36 in Experiment I (Cuttack, wet season 1991).

Yield and Yield Attributes

Yield and yield attributes are presented in Table 6. Grain yield was lowest in T1 and highest in T4. Grain yield of T2 was not much lower than T4. A crop with a low initial N status at PI (T2) was therefore more effective in using the second fertilizer split than a crop with high initial N status at PI (T4). A similar trend was observed for other yield attributes like panicle number, filled grain number and 1000 grain weight. Application of N at PI increased the harvest index. The increase in harvest index due to application of N at PI was greater for a crop with a low initial N status (T2) than for a crop with a high initial N-status (T4).

In general, the percentage of unfilled grains in all treatments was high (i.e. around 30%), possibly due to the low solar radiation levels in the wet season.

Experiment II

Dry Weight of Plant Organs

Dry weight of leaves, stems, roots, panicles and total crop biomass are presented in Tables 7 and 8. Total leaf and stem dry weights gradually increased with crop age and reached a maximum at the beginning of the grain filling stage in all treatments except for T1. If N was applied at late growth stages (T2, T3, T4) leaf and stem dry weights were smaller than if N was applied early (T5, T6, T7, T8, T9, T10 and T11). High stem weight at maturity was recorded for T9, T10 and T11 which received higher doses of N at initial growth stages. The crop which received nitrogen at all growth stages (T6) produced highest leaf and stem weight at harvest. The weight of roots gradually increased until 48 DAT in all treatments and did not show any definite trend afterwards.

The early difference in dry weight of roots between different treatments did not exist at harvest. For all treatments, root weights were very similar, except for T1 and T2 for which root weights were rather low. It was further noted that the crop which received higher amounts of nitrogen at transplanting stage produced higher leaf and stem weight initially (up to 48 DAT) but produced comparatively less leaf weight at a later growth stage. A delay in flowering was noticed in Treatments T2, T3, T4, T5 and T6.

Table 7. Dry weight of leaves and stems (kg/ha) of rice cvar IR36 in Experiment II (Cuttack, dry season, 1993) at different days after transplanting (DAT). Treatment codes are explained in Table 2.

Treatment	0 DAT	18 DAT	39 DAT	48 DAT	62 DAT	69 DAT	92 DAT
	Biomass of leaves (kg/ha)						
T1	28	87	397	672	1083	631	528
T2	28	86	422	733	1172	1402	1047
T3	28	109	478	900	1483	1650	1206
T4	28	109	674	1247	1622	1944	1411
T5	28	110	950	1366	1777	2155	1625
T6	28	125	1050	1356	1977	2298	1703
T7	28	139	997	1472	1860	2211	1528
T8	28	138	1047	1639	1900	2264	1586
T9	28	133	1152	1708	1877	2058	1508
T10	28	148	1261	1722	1776	1863	1455
T11	28	155	1208	1609	1650	1667	1403
	Biomass of stems (kg/ha)						
T1	32	85	622	924	2417	1933	1417
T2	32	85	633	950	2522	2897	1872
T3	32	86	621	980	2883	3398	2171
T4	32	91	752	1325	2902	3492	2514
T5	32	108	969	1419	3196	3904	2875
T6	32	128	1061	1489	3650	4138	3052
T7	32	145	1022	1530	3594	4066	2796
T8	32	156	1028	1819	3922	4164	2925
T9	32	154	1072	1805	3838	4095	3005
T10	32	169	1114	1841	3966	4253	3011
T11	32	166	1150	1849	3883	4369	3008

Carbohydrate remobilization

Post flowering reduction in stem biomass generally indicates a translocation of carbohydrates to the storage organs. The relative contributions from leaves, stems and new (post-flowering) photosynthesis to final grain yield are shown in Figure 4. In all treatments, the stem biomass had decreased by 1.0-1.2 t/ha by the time of harvest, as compared to the maximum stem biomass attained around flowering (Table 7). In Treatment T1 remobilization from stems accounted for 30% of final grain yield. This figure decreased to roughly 15% as a result of fertilizer application which was associated with increased post flowering photosynthesis.

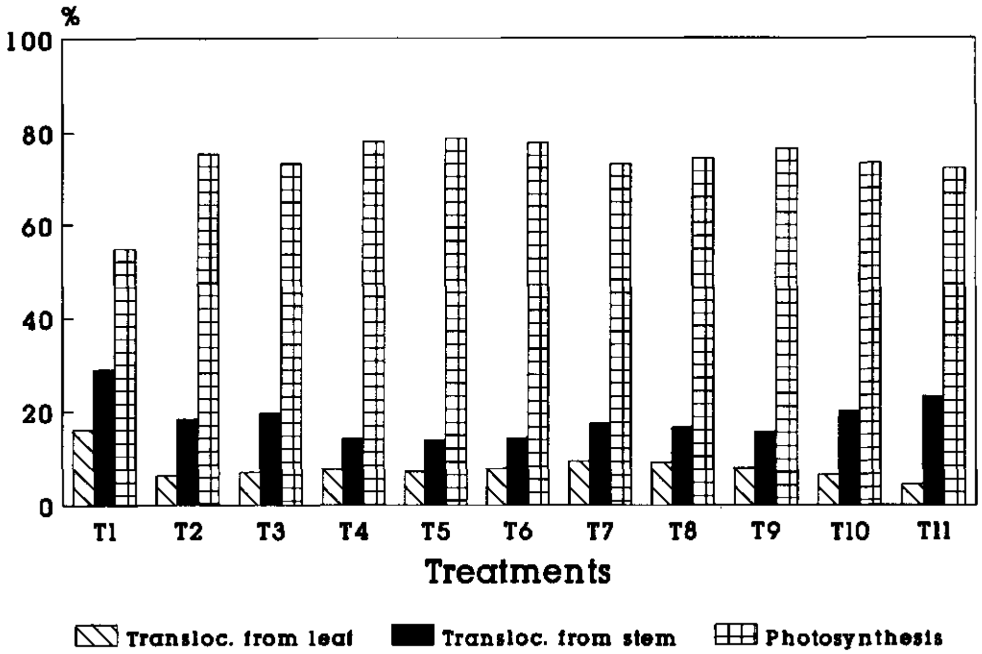

Figure 4. Contribution of translocated carbohydrates from leaf and stem and post flowering photosynthesis to final yield in Experiment II (Cuttack, dry season 1993).

Table 8. Dry weights of roots, panicles and grains, and total dry matter (kg/ha) of rice cvar IR36 in Experiment II, Cuttack, dry season, 1993.

Treatment	0 DAT	18 DAT	39 DAT	48 DAT	62 DAT	69 DAT	92 DAT
	Biomass of roots (kg/ha)						
T1	16	72	275	564	764	473	453
T2	16	85	281	571	783	672	616
T3	16	80	304	611	794	875	807
T4	16	80	402	922	888	1053	858
T5	16	102	425	875	933	1083	819
T6	16	110	497	981	938	1083	849
T7	16	128	569	975	961	985	836
T8	16	136	553	1052	971	1061	853
T9	16	144	570	903	850	936	804
T10	16	144	633	927	833	901	835
T11	16	150	625	842	805	814	806
	Biomass of panicles+grains (kg/ha)						
T1					226	1389	3655
T2					-	1139	5978
T3					-	1179	6571
T4					-	2069	7039
T5					-	2113	7550
T6					-	2019	7750
T7					53	1778	7522
T8					105	1869	7633
T9					100	1513	7433
T10					135	1605	6711
T11					150	1919	6505
	Total crop biomass (kg/ha)						
T1	76	244	1294	2160	4490	4426	6053
T2	76	256	1336	2254	4477	6110	9573
T3	76	275	1403	2491	5160	7102	10755
T4	76	280	1828	3494	5412	8558	11822
T5	76	320	2344	3660	5906	9255	12869
T6	76	363	2608	3826	6565	9538	13354
T7	76	412	2588	3977	6468	9040	12682
T8	76	430	2628	4510	6898	9358	12997
T9	76	431	2794	4416	6665	8602	12950
T10	76	461	3008	4490	6710	8622	12012
T11	76	471	2983	4300	6488	8769	11722

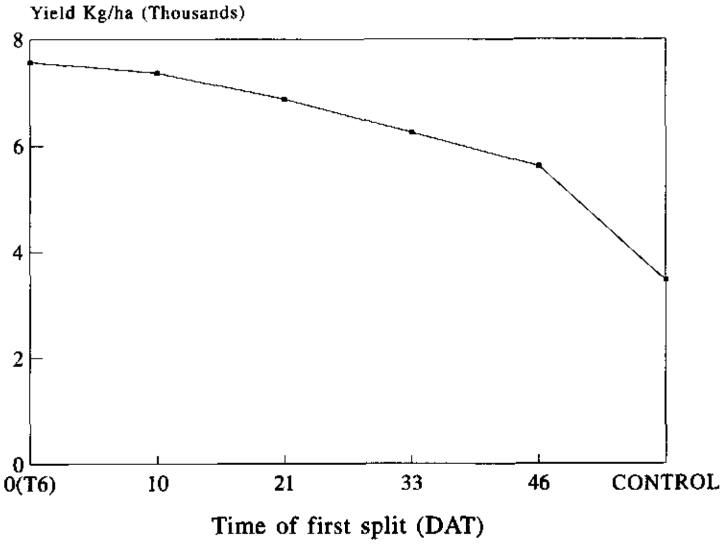

Figure 5. Final grain yield as a function of timing of the first N split in Experiment II (Cuttack, dry season 1993).

Table 9. Yield and yield components of rice cvar IR36 as affected by split application of nitrogen in Experiment II (Cuttack, dry season, 1993).

Treat-ment	Grain yield	Straw yield	HI	PAN	F-GR	UNF-GR	UNF-GR	1000 Grain weight
	kg/ha^{-1}	kg/ha^{-1}		No/m^{-2}	No/m^{-2}	No/m^{-2}	(%)	(g)
T1	3453	2535	0.57	325	16073	5417	25.2	21.10
T2	5612	3255	0.59	415	25255	8067	24.2	22.15
T3	6245	3643	0.58	425	26498	7940	23.1	23.20
T4	6871	4233	0.58	451	28683	7881	21.6	23.60
T5	7367	4530	0.57	465	30571	7430	19.6	23.60
T6	7570	4704	0.57	470	31269	7198	18.7	23.90
T7	7295	4566	0.58	480	30971	8042	20.6	23.00
T8	7456	4894	0.57	485	31198	8449	21.3	23.00
T9	7000	5170	0.54	475	29481	9585	24.5	22.20
T10	6205	5286	0.52	454	28081	9539	25.4	21.35
T11	5870	5219	0.50	438	26029	9593	26.9	21.20

HI = harvest index PAN = panicles F-GR = filled grains
UNF-GR = unfilled grains No m^{-2} = number per m^2.

Yield and Yield Attributes

Grain yield of rice and yield components are presented in Table 9. Highest yields were obtained for T5, T6, T7 and T8. The yield differences between these treatments were not statistically significant. T9, T10 and T11 produced high straw yields but relatively low yields resulting in low harvest indices. The harvest index increased for treatments where nitrogen was applied at later growth stages (T2 to T5).

Grain yield plotted against the time of first split (Figure 5) showed that the delay in application of the first split from transplanting to 46 DAT reduced final grain yield to a maximum of about 2 t/ha.

Conclusions

Experiment I

Application of N at PI increased dry weights of leaf, stem, root and panicle and also their N content and total N uptake. The magnitude of increase was larger for a crop with a low initial N status than for a crop with high initial N status.

The recovery percentage of total applied N as well as of the second N split was larger for a crop with a low initial N status than for a crop with a high initial N status.

Experiment II

Highest yields (i.e. around 7.5 t/ha) were obtained when N was applied in 5 or more splits; skipping a basal application or an application either at flowering or in between PI and flowering resulted in only minimal yield reduction with respect to the 7 split treatment.

Contribution of post-flowering photosynthesis to final grain yield was about 75% if N was applied to the crop. This percentage dropped to 55% when no fertilizer was applied. Remobilization from stems contributed up to 30% of final grain yield in the absence of fertilizer application. The absolute value of estimated remobilization from stems was about 1 t/ha in all treatments.

Delay in nitrogen application beyond the active tillering stage drastically reduced grain yield by reducing the number of panicles. Similarly, the omission of nitrogen application after active tillering stage to a crop that received N in the early stages reduced grain yield by reducing the harvest index and increasing the number and percentage of unfilled grains.

Postponing the first split upto 46 DAT reduced final grain yield progressively by about 2 tons/ha. Application of N during vegetative growth (upto PI) increased the number of panicles but reduced the number of filled grains, thousand-grain weight and harvest index.

Postponing the first application of N until PI increased the number of filled grains, thousand-grain weight and harvest index but reduced the number of panicles.

Application of N in both the vegetative and the panicle development stage resulted in a high number of panicles, with a large percentage of filled grains and a high thousand-grain weight and therefore largest yields. In general, the percentage of unfilled grains was quite large in all treatments which may be due to insufficient incoming solar radiation during the grain filling period.

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Nitrogen and rice: Uptake and recovery of applied nitrogen

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Abstract

Two replicate field experiments were conducted from 1991 to 1993 at the Soil and Water Management Research Institute, Thanjavur, Tamil Nadu, India. The effect of different N application strategies, i.e. 0, 50, 100 and 150 kg N/ha at 10 days after transplanting (DAT) and 0 and 100 kg N/ha at panicle initiation (PI) on growth, N uptake (N_c) and grain yield of rice cvar CR 1009 was investigated. A third experiment was conducted to compare the effect of urea N and organic N from farm yard manure (FYM), green manure (GM) (*Sesbania rostrata*) and Azolla (*A. pinnata*) on growth, N_c and yield in cvar IR64 during July to October, 1992. Inferences were drawn from the results of these three experiments on N_c and relations between N_c and N translocation, N_c and yield attributes, and N_c and yield.

N_c at any one stage of the crop was linearly related to N applied at 10 DAT. Application of 100 kg N at PI resulted in a 2 to 3 fold increase in N_c depending on the existing crop and root biomass and N_c at PI. N_c in organic manure treatments were in the order of GM>Azolla>FYM. GM maintained the highest N_c until flowering (F), afterwards the highest N_c was observed in 10 split urea treatment. Split application resulted in more N_c than single dose. Maximum rate of N uptake (6.6 kg/ha/d) was observed from urea N during the first half of the PI-F phase in CR1009. The highest N uptake rate among organic N sources was 3.6 kg/ha/d which occured for GM during the second half of the PI-F phase in IR64. Translocation of N from leaves made up 63% and 58% of the remobilisation pool in cvars CR1009 and IR64, respectively. Up to 25% of maximum N_c reached ($N_{c,max}$) was lost from the crop during grain filling in CR1009. The relation between N loss and $N_{c,max}$

was less obvious in IR64. Apparent N recovery (ANR) from urea was 23 to 69% and 13 to 49% when evaluated at F and harvest (H) stages, respectively. Very high values of ANR (65-87%) were obtained from 100 kg N applied at PI when evaluated on the basis of $N_{c,max}$. Panicle and spikelet numbers and yield all per unit area were positively related to $N_{c,max}$. Unfilled spikelet number increased with $N_{c,max}$ up to 125 kg N/ha, beyond which it dropped with increasing $N_{c,max}$. Grain yield per unit amount of $N_{c,max}$ recorded for CR1009 was about the same as in IR64. Yield potential of CR1009 during 1992-1993 was reduced because N uptake stalled from mid-tillering to PI.. The N uptake during later phases could not make up for this setback.

Introduction

Nitrogen (N) is a very important nutrient for the rice plant and largely determines the yield level. A large section of rice literature illustrates the effects of N availability on rice N uptake, growth and grain yield (e.g. Patrick et al., 1974; Marschner, 1986). The distribution of N in the rice plant after it is taken up and especially the remobilisation of N from leaves and stems have also been illustrated (Muhammad et al., 1974). Under conditions of changing agronomic practices, induced by rising fertilizer cost, reduced availability of water, and increasing concern about sustainability issues, a thorough understanding of basic mechanisms underlying rice-N relations is required. Such understanding allows timely adjustment of recommendations for crop and soil management.

In South India's Cauvery delta, Tamil Nadu, three N-fertilizer application strategies are currently practiced in rice production:

1. Applying 40% of the recommended amount of N as basal, and the remaining 60% in equal doses at active tillering (AT), panicle initiation (PI) and flowering (F) stages of the crop.
2. Applying half of the recommended amount of N as basal and the other half in two equal splits at AT and PI stages.
3. Applying the recommended amount of N in six equal splits: at transplanting (TP), 10 days after transplanting (DAT), AT, maximum tillering (MT), PI and F stages, respectively.

We studied responses of rice to fairly extreme N application strategies. This paper reports three experiments. Two experiments were conducted to assess the influence of a high dose of N at PI stage, i.e. 100 kg/ha (four times higher than what is normally applied) on N uptake, recovery, growth and yield of the rice crop. Recently the use of organic sources of N has become more popular in an attempt to reduce the cost of N-fertilizer. Therefore the third study reported here was undertaken to find out the effects of supplying the full recommended dose of N at transplanting, in the form of organic manures, on N uptake, recovery, growth and grain yield.

Across the three experiments, the relations between N uptake and yield and between N uptake and yield determining characteristics (productive tiller number, spikelet number and percentage of unfilled grains) are presented. Some observations are made on N translocation and loss from the crop.

Materials and methods

Three field experiments were conducted at the Soil and Water Management Research Institute, Thanjavur, Tamil Nadu, India during the years 1991-1993. The soil of the experiment site was sandy loam, Typic Haplustalf, low in organic carbon (0.43%), available N (51 ppm), available potassium (47 ppm) and CEC (10.2 meq/100 g), high in Bray I phosphorus (79.2 ppm). The general details of the three field experiments are given in Table 1. The treatments in Experiments 1 and 2 are specified in Table 2. In Experiments 1 and 2, urea (46% N) was used as the sole N source. Urea granules were broadcasted for both 10 DAT and PI applications and incorporated at 2 to 3 cm depth. All the treatments received 90 kg P_2O_5/ha as basal dressing and 60 kg K_2O/ha, half as basal and the other half at PI.

Rice plants were sampled on 0 (TP), 10, 24 (AT), 43 (MT), 59 (PI), 75, 91 (F), 108 and 121 (H) DAT for Experiment 1. Sampling days for Experiment 2 were 0 (TP), 37 (MT), 69 (PI), 94 (F) and 119 (H) DAT. For measurement of biomass, three hills were selected which had a tiller number equal to the average tiller number assessed from tiller counting on 20 hills per plot. Care was taken that no loose or dead leaf material was lost from the plants during sampling. In Experiment 1 the plants were separated into roots, stems, green leaves, dead leaves and panicles. N content of all the plant organs was measured by micro Kjeldhal method. In Experiment 2 the entire plant (including roots) was treated as a single entity to record biomass production and N content.

Table 1. Experimental details.

	Expt 1	Expt 2	Expt 3
Variety	CR1009	CR1009	IR64
Seedling age	31 d	30 d	27 d
Date of TP	12 Sep. '91	11 Sep. '92	5 Jul. '92
Spacing	20x15cm	20x15cm	15x10cm
Seedlings/hill	1	1	1
Time of PI	59 DAT	69 DAT	42 DAT
Time of F	91 DAT	94 DAT	63 DAT
Field duration	121 d	119 d	93 d
Date of H	11 Jan. '92	8 Jan. '93	16 Oct. '93
Design	RBD	RBD	RBD
Replications	4	4	5

Table 2. Treatment details of Experiments 1 and 2.

Treat.no.	N levels (kg/ha)		
	at 10 DAT	at PI	Total
T1	0	0	0
T2	0	100	100
T3	50	0	50
T4	50	100	150
T5	100	0	100
T6	100	100	200
T7	150	0	150
T8	150	100	250
T9	150 kg in six equal splits: at TP, 10 DAT, AT, MT, PI and F, respectively		

Table 3. Treatment details of Experiment 3.

Treat no.	N source	Characteristics of N Source moisture (%)#	 total N (%)*	 NH_4-N (ppm)*	 NO_3-N (ppm)*	quantity (Mg/ha)	Total N (kg/ha)
T1	FYM	53.6	0.66	18.8	1256.3	40.8	125
T2	GM	71.5	2.04	<14	<14	21.5	125
T3	Azolla	84.5	3.93	2533.9	115.3	20.5	125
T4	Urea, 10 splits	ND	46.0	0.0	0.0	0.27	125
T5	Urea, 4 splits	ND	46.0	0.0	0.0	0.27	125
T6	No N application						0

\# by wet weight basis   * by dry weight basis   ND not determined

Table 3 summarizes the treatment details of Experiment 3. Green manure (GM) was applied 15 days prior to transplanting. Shoot biomass of *Sesbania rostrata* at the start of flowering stage was cut into 10 to 15 cm pieces and distributed on the puddled soil and incorporated. Mass multiplication of Azolla (*A. pinnata*) was started one month before transplanting the rice seedlings, and the Azolla harvests were stored under shade. Farm yard manure (FYM) was applied in the form of one year old compost. FYM and Azolla were applied and incorporated on the day prior to transplanting. Urea was used as the N source in Treatment 4 (12.5 kg N /ha each time on 0, 7, 14, 21, 29, 35, 42, 49, 56 and 63 DAT) and in Treatment 5 (50 kg at planting and 25 kg each time at AT, PI and F). All treatments received 90 kg P_2O_5/ha as basal dressing and 60 kg K_2O/ha, half as basal and the other half at PI. The plants were sampled on 0 (TP), 14, 21 (AT), 29, 35 (MT), 42 (PI), 49, 56, 63 (F), 70, 78 and 93 (H) DAT. Sampling, sample processing and N estimation were done as explained under Experiment 1.

Results and discussion

N uptake from applied urea (Experiments 1 and 2)

The total amount of N present in the crop (roots included) is here referred to as N_c (kg N/ha). N_c is interpreted as the net N uptake. N_c in the treatments that received no fertilizer N at PI stage was proportional throughout the season with the amount applied at 10 DAT ($r = 0.8654^*$ to 0.9998^{**}). The maximum value of N_c ($N_{c,max}$) was reached at F stage (91 DAT) in Treatments T2, T5, T7, T8 and T9. Treatments T3, T4 and T6 recorded $N_{c,max}$ at 108 DAT. While there was a slight N uptake during grain filling in the control treatment, N_c dropped after F stage in all other treatments in Experiment 1 (Figure1a). N_c in Experiment 2 followed a similar pattern. There, however, N_c stayed at the same level from MT-PI phase (Figure 1b). This was reflected in the grain yields which were generally lower in the Experiment 2 as shown later in this paper. This uptake reduction is attributed to the excessive rainfall received during that period which may have caused high N losses by leaching from the relatively coarse textured, low CEC soil. Of the two replicate Experiments 1 and 2, only the results of Experiment 1 will be discussed in the remainder of this paper unless mentioned otherwise, because only limited observations were made in Experiment 2.

The slope of the relation between the amount of N applied and N_c increased over time and then decreased. The N uptake during the vegetative phase was followed by a net N loss during grain filling in all treatments except in the control treatment. N losses will be addressed in a later part of this paper for all three experiments and treatments.The distribution of N uptake over the distinguished phases is given in Table 4.

There was a positive relation between the amount of N applied at 10 DAT and the increment in N_c over the TP-AT and AT-MT phases (Figure 2a). A similar pattern was observed in Experiment 2 (Figure 2b). Afterwards the trend was not consistent and even negative values were recorded for the increment in N_c, reflecting loss of N from the crop in both experiments. The treatments which received N at PI (T2, T4, T6 and T8) showed a steep increase in N_c. Application of 100 kg N at PI stage resulted in the largest uptake between PI and MF stages. The N uptake rate during this period was 5.4, 5.0, 5.7 and 6.6 kg ha^{-1} d^{-1} in Treatments T2, T4, T6 and T8, respectively. In spite of the high N application at PI stage, Treatments T2, T4, T6 and T8 recorded lower N uptake when compared to the other treatments during MF-F phase. This suggests that N application at PI stage 'saturated' the crop with N before MF stage. The status of the crop at MF stage is here characterized in terms of N_c, which varied for these high N treatments from 129 to 183 kg N/ha, with corresponding leaf N contents of 2.36 to 2.56% and leaf biomass ranging between 2218 and 3200 kg/ha.

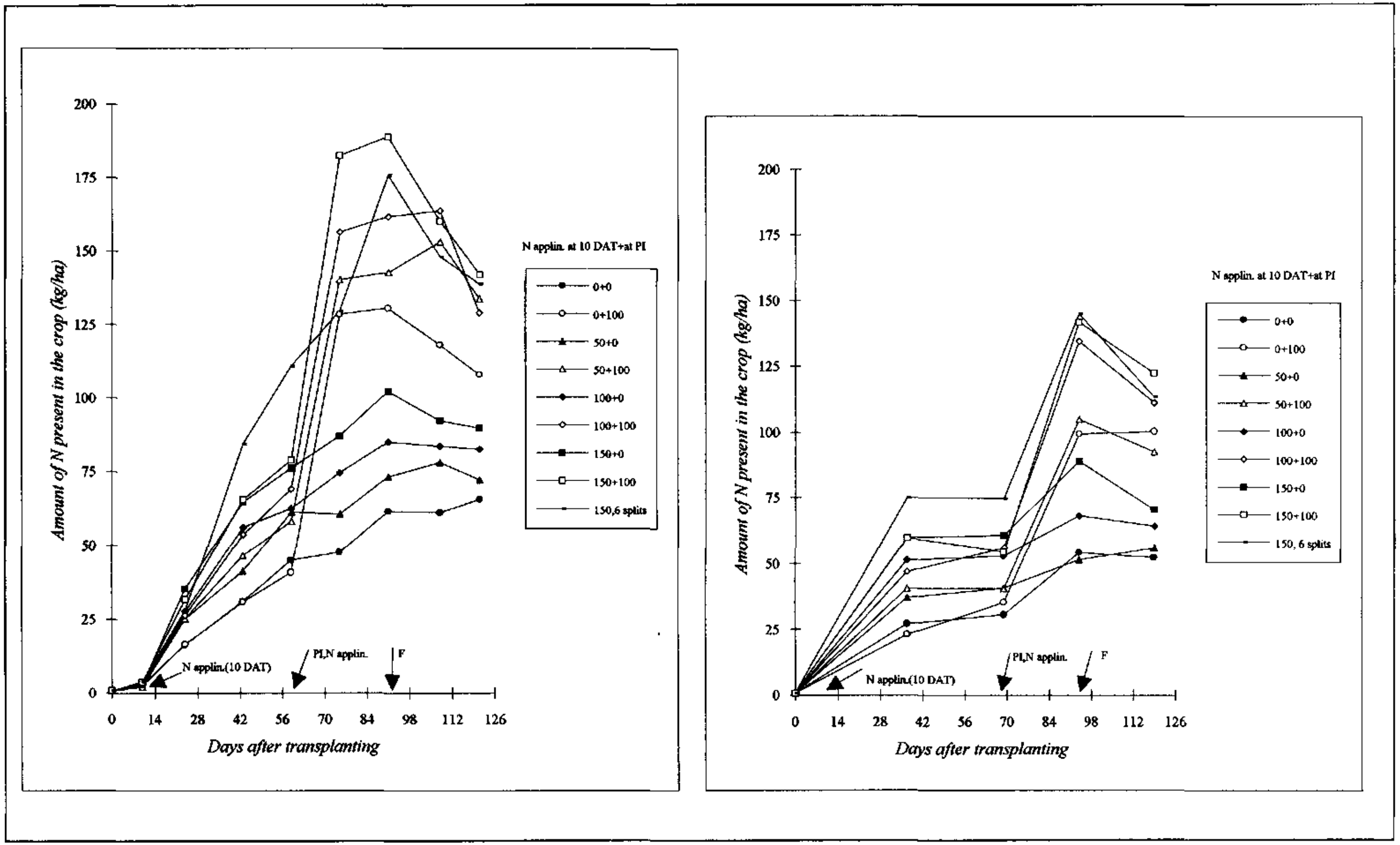
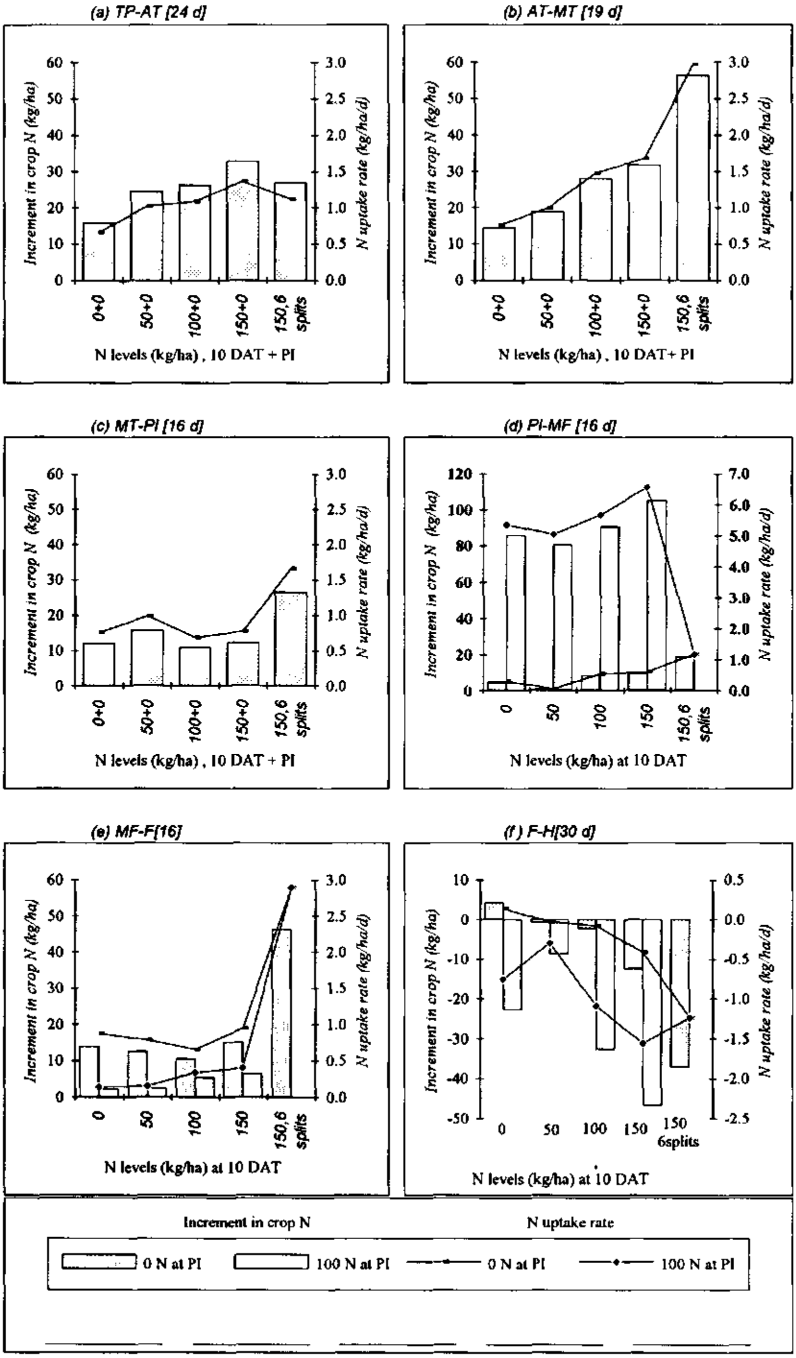


Figure 1. Effect of graded levels of N application at 10 DAT and a high dose of N application at PI on the amount of N in crop in rice cvar CR 1009 during wet season at Thanjavur. Left: (a) 1991-'92 (Experiment 1); right (b) 1992-'93 (Experiment 2).


(a) TP-AT [24 d]

(b) AT-MT [19 d]

(c) MT-PI [16 d]

(d) PI-MF [16 d]

(e) MF-F[16]

(f) F-H[30 d]

Figure 2a. Effect of graded levels of N application at 10 DAT and a high dose of N application at PI on the incremental N uptake during different phases of rice cvar CR1009, wet season, 1991 - 1992, Thanjavur (Experiment 1).

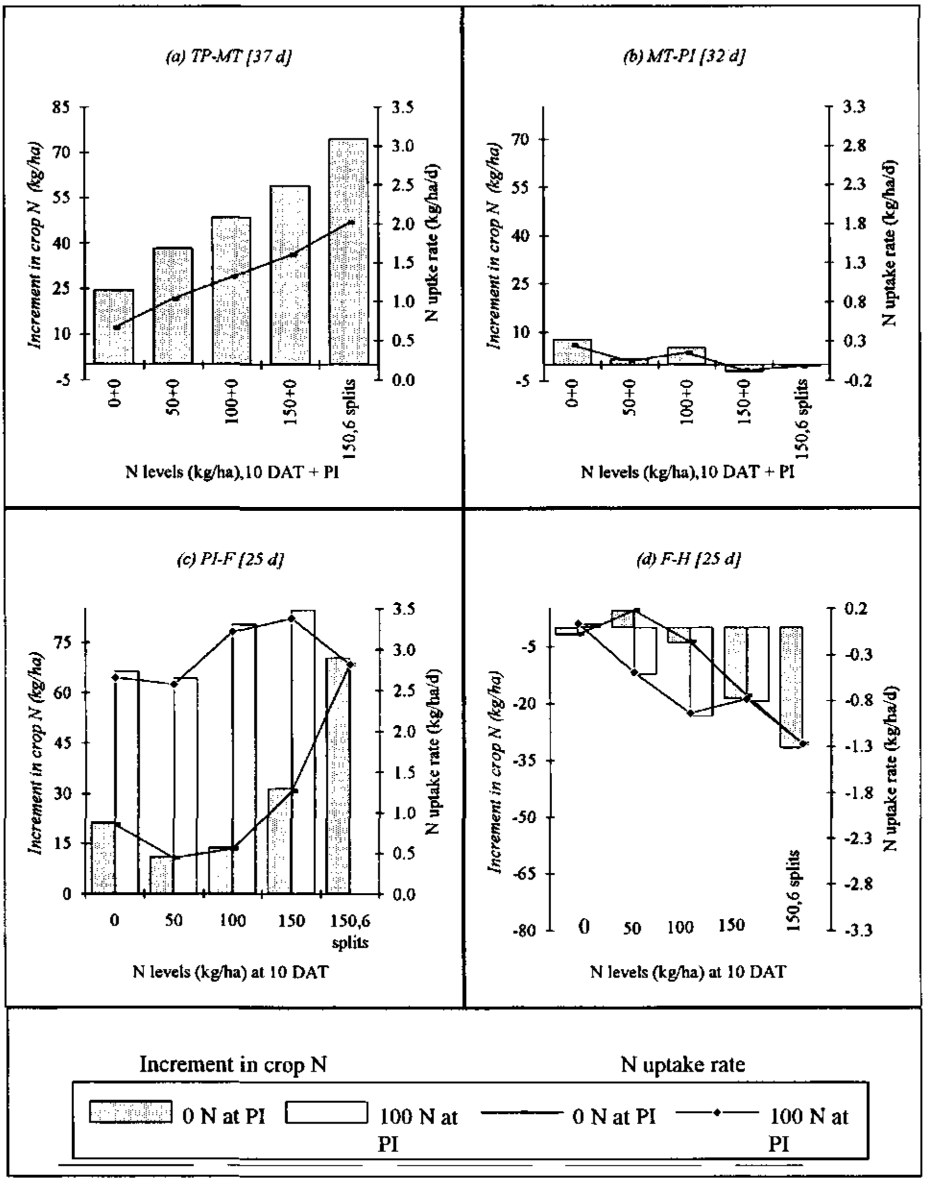


Figure 2b. Effect of graded levels of N application at 10 DAT and a high dose of N application at PI on the incremental N uptake during different phases of rice cvar CR1009, wet season, 1992 - 1993, Thanjavur (Experiment 2).

Table 4. Fraction of N_c, relative to $N_{c,max}$ gained or lost in rice cvar CR1009 during 1991-1992 wet season (Experiment 1) at Thanjavur.

N at 10 DAT + PI	$N_{c.max}$	Date of $N_{c.max}$	Fraction of $N_{c.max}$ gained					
(kg/ha)	(kg/ha)	(DAT)	TP-AT	AT-MT	MT-PI	PI-MF*	MF*-FL	FL-H
0+0	65.87	121(H)	0.24	0.22	0.18	0.07	0.21	0.06
0+100	130.76	91(F)	0.12	0.11	0.09	0.65	0.02	-0.17
50+0	78.18	108	0.31	0.24	0.20	0.01	0.16	-0.01
50+100	153.27	108	0.16	0.12	0.10	0.53	0.02	-0.06
100+0	85.07	91(F)	0.31	0.33	0.13	0.10	0.12	-0.03
100+100	163.92	108	0.16	0.17	0.07	0.55	0.03	-0.20
150+0	102.28	91(F)	0.32	0.31	0.12	0.09	0.15	-0.12
150+100	188.97	91(F)	0.17	0.17	0.07	0.56	0.03	-0.25
150,6 splits	176.06	91(F)	0.15	0.32	0.15	0.11	0.26	-0.21

* MF, mid flowering (75 DAT) is defined here as the stage that divides the period from PI to F into two equal periods.

In Table 5, estimates are presented of the amounts of N that were contributed by three external N sources to N_c by the time ($t_{N,max}$) N_c had reached its maximum value, $N_{c,max}$. The following simplifying assumptions were made in deriving these estimates:

1 The amount of N derived from soil equals $N_{c,max}$ attained in the control treatment (T1).
2 The amount of N derived in Treatment Ti from N applied at 10 DAT equals $N_{c,max}$ (Ti) - $N_{c,max}$ (T1), where i = T3, T5 and T7, the treatments which received no N at PI stage.
3 The amount of N derived in Treatment T(i+1) from N applied at PI stage equals $N_{c,max}$ (T(i+1)) - $N_{c,max}$(Ti), where i = T1, T3, T5 and T7.

The table includes total biomass, root biomass, crop N%, leaf N% and N_c at PI stage to characterize the status of the crop at the time of second N application. As shown in this table, that status largely affects the estimated uptake from the second N application. Fertilizer N-recovery is discussed later in this paper.

Table 5. Crop status at PI, and estimated contributions of soil N, first split, and second split N applications, respectively to $N_{c,max}$ in rice cvar CR1009, wet season, 1991 - 1992, Thanjavur.

N applied at 10 DAT	Crop status at PI					$N_{c.max}$ (kg/ha) derived from		
DAT (kg/ha)	Biomass (kg/ha)	Root (kg/ha)	Crop N (%)	Leaf N (%)	N_c (kg/ha)	Soil	First split	Second split
0	4863	1063	0.884	1.566	43	66	0	65
50	6311	1276	0.947	1.746	60	66	12	75
100	7066	1753	0.932	1.714	66	66	19	79
150	7684	1650	0.971	1.692	78	66	36	87

N uptake from organic sources (Experiment 3)

Figure 3 shows the course of crop N uptake observed for different organic N sources. The GM treatment showed the highest N_c values up to F stage, but was surpassed after F stage by the 10 split urea treatment. N_c decreased in the order GM > Azolla > FYM for the three organic sources, at any stage of the crop. The poor performance of Azolla and FYM may have been caused by losses of N via leaching and denitrification. These manures showed a relatively high degree of decomposition at the time of application as evident from their mineral N content (Table 3). The addition of large amounts of organic matter through FYM and Azolla could, alternatively, also have increased immobilization (Williams et al., 1968).

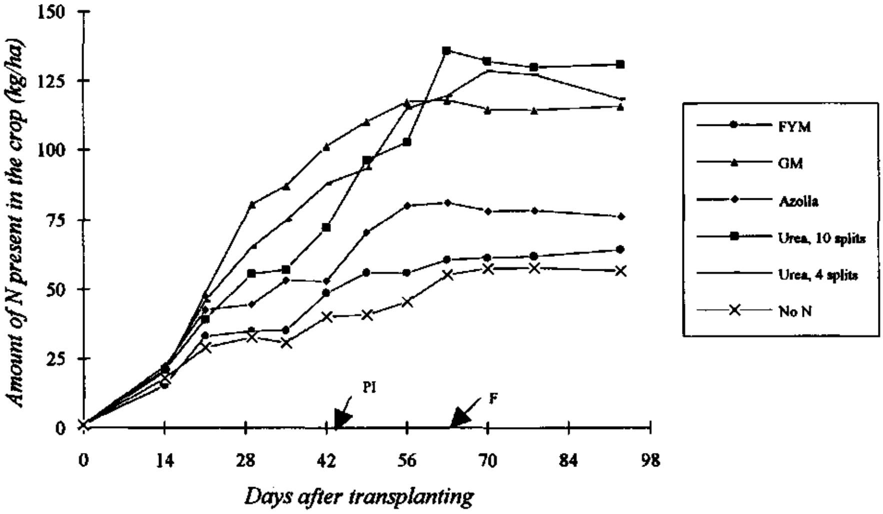


Figure 3. Effect of different sources of N on the amount of N in crop in rice cvar IR64 during July - October, 1992, Thanjavur (Experiment 3).

The largest N_c increment was registered during TP-AT phase (Figure 4) for all the treatments. The N uptake rates are also given in Figure 4. The highest uptake rate (3.6 kg/ha/d) was observed in the 10 split urea treatment, at MF-F phase. Among the organic N sources, the highest uptake rate (2.5 kg/ha/d) was registered in GM treatment, during the TP-AT phase. None of the treatments showed a significant post-F uptake, except for the four split urea treatment.

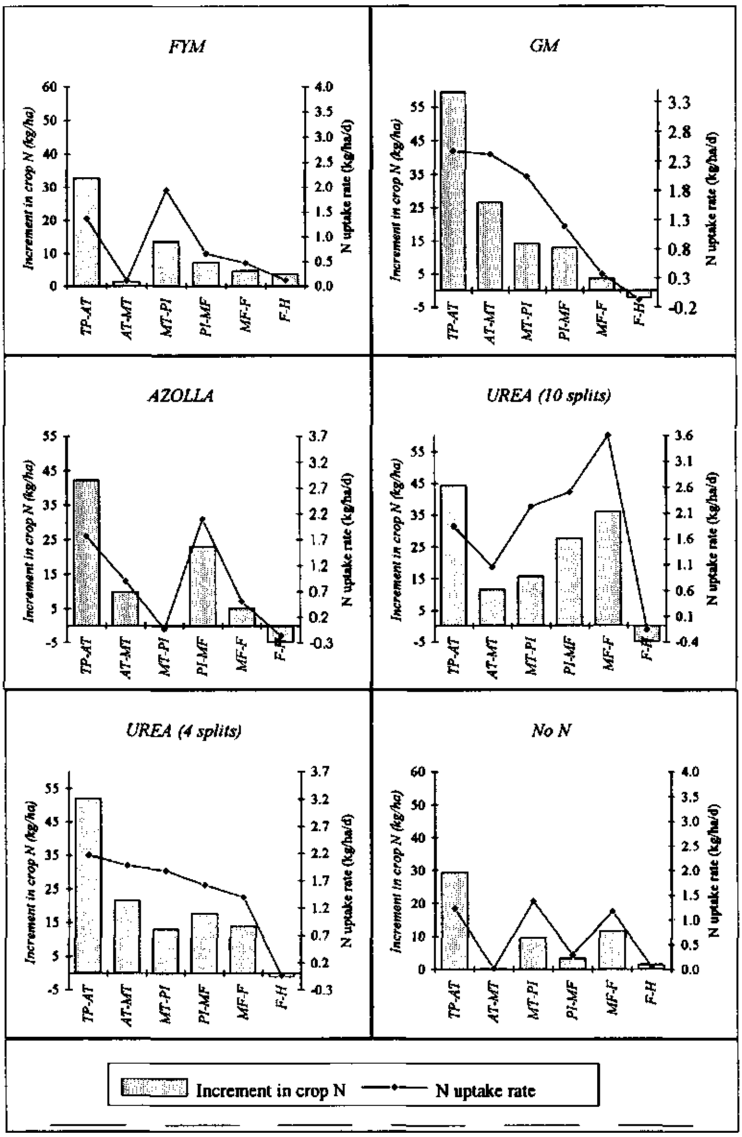
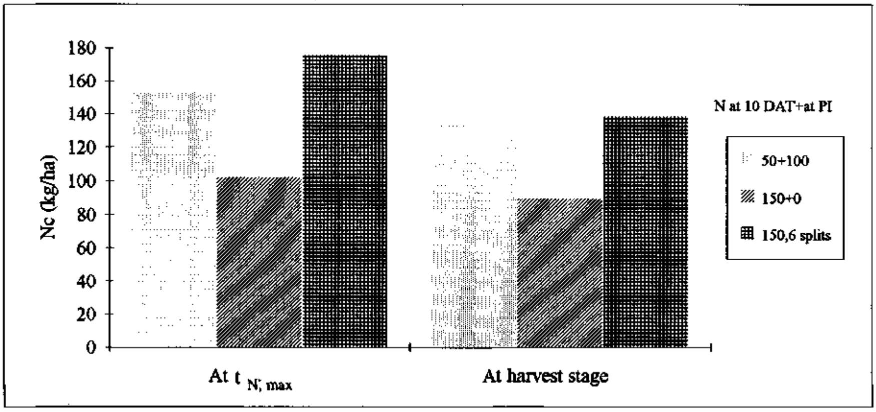
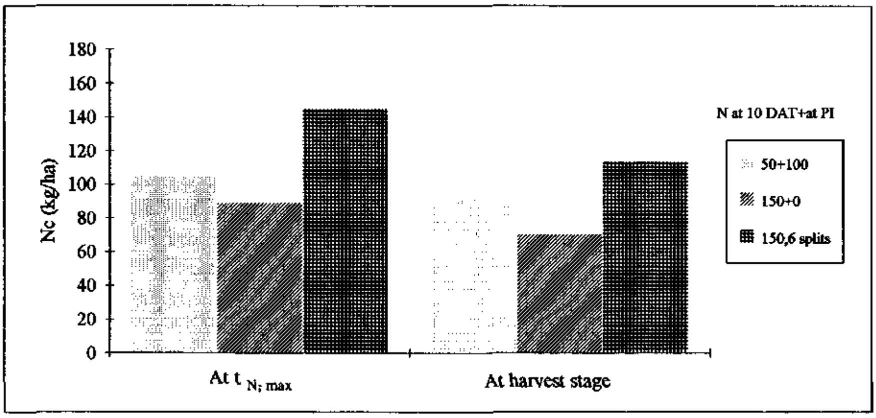


Figure 4. Effect of different sources of N on incremental N uptake and N uptake rate during different phases of rice cvar IR64, July - October, 1992, Thanjavur (Experiment 3).

(a) CR1009, wet season, 1991-'92



(b) CR1009, wet season, 1992-'93



(c) IR64, July - October, 1992

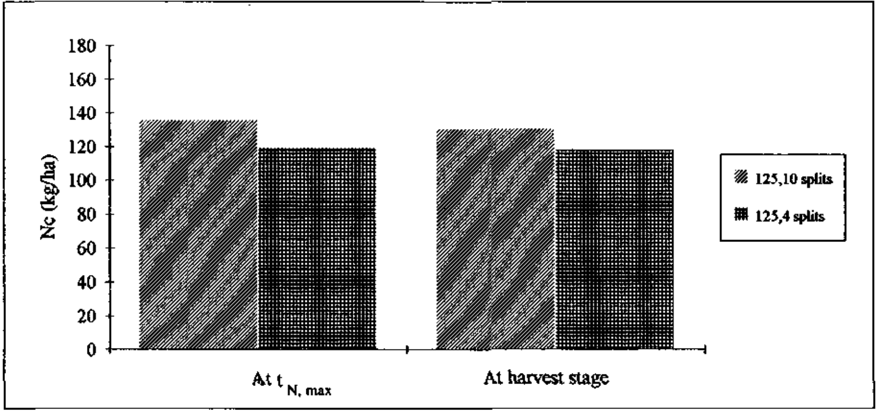


Figure 5. Effect of timing of urea N application on the amount of N in crop (N_c)in rice cvars CR1009 and IR64, Thanjavur (Experiments 1, 2 and 3).

Effect of timing of urea N application (Experiments 1, 2 and 3)

Figure 5 shows the effect of timing of urea N application on the $N_{c,max}$ and N_c at H stage (N_{cH}). Each of the treatments T4, T7 and T9 in Experiments 1 and 2 received 150 kg N/ha by different types of splits. Single dose of N at 10 DAT (T7) recorded the lowest value and six split application (T9) recorded the highest value for $N_{c,max}$ and N_cH. Application of 1/3 at 10 DAT and 2/3 at PI (T4) was more effective in increasing the N_c than applying the entire N at 10 DAT for rice cvar CR1009. The results from the Treatments 4 and 5 in Experiment 3 (cvar IR64) showed that application of 125 kg N/ha in 10 equal splits (T4) at weekly intervals starting from planting was superior (both in N_c and grain yield) to the current practice of applying 2/5 as basal and 1/5 each at AT, PI and F stages (T5).

Translocation of leaf and stem N (Experiments 1 and 3)

The total amount of N translocated from leaves (kg N/ha) is here defined as the difference between leaf N content (kg N/ha) at F stage and the leaf N content at H stage. Likewise translocation from the stem is calculated. The sum of these two is used for grain N supply, but some amount from this pool is lost. A linear relationship was observed between the amounts of N translocated after F stage from stems and leaves. Their relative contributions to this translocation pool were 63% (leaves) and 33% (stems) in CR1009, and 58% (leaves) and 42% (stems) in IR64 (Figure 6). N translocated from leaf and stem (with reference to the maximum values of N in the respective plant organs) was linearly related to $N_{c,max}$ (Figure 7). On an average (both cvars), 32% of $N_{c,max}$ was remobilized from the leaves and 24% from the stems.

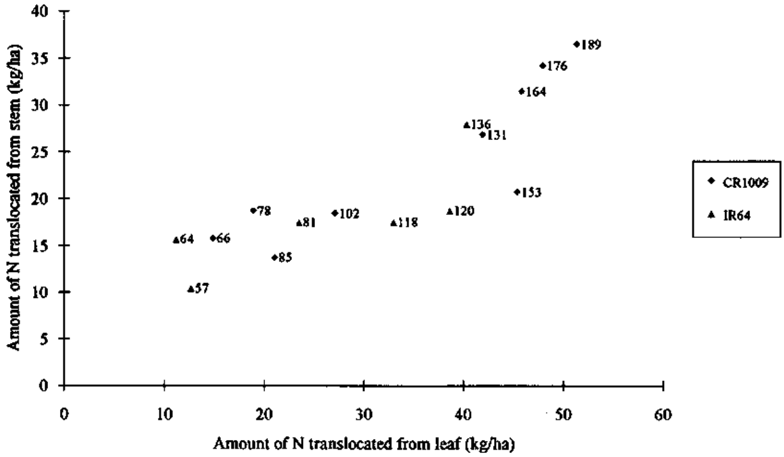
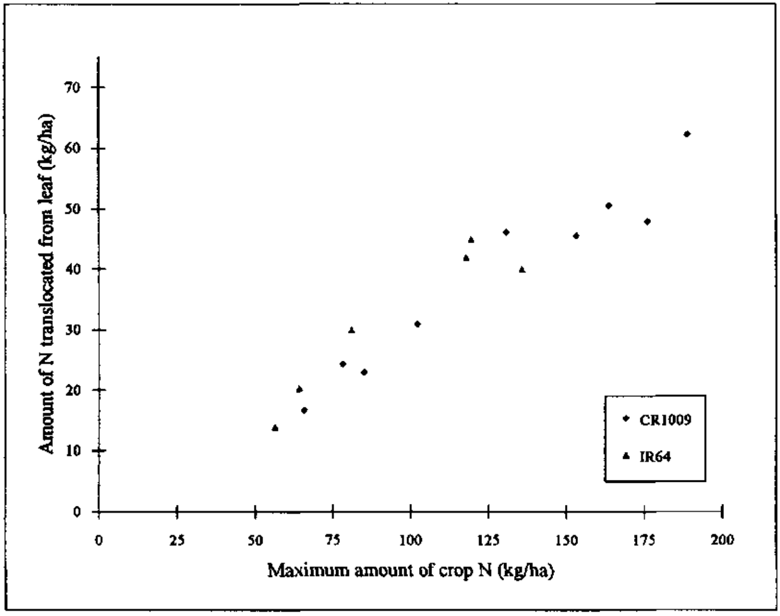


Figure 6. Relationship between amount of N translocated from leaf and from stem after flowering stage in rice cvars CR1009 (wet season, 1991 - 1992) and IR64 (July - October, 1992) at Thanjavur (Experiments 1 and 3). Figures attached to symbols are $N_{c,\ max}$ values.

(a) From leaf



(b)From stem

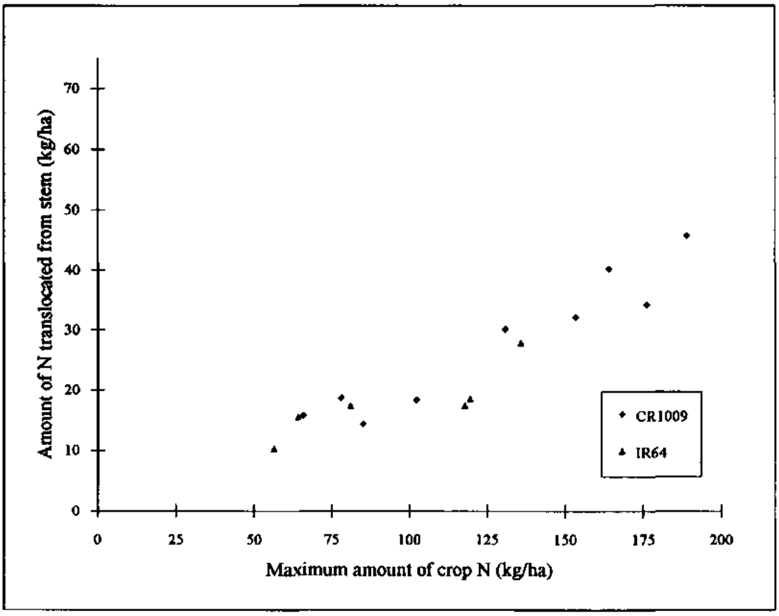


Figure 7. Relationship between N translocated from leaf and from stem and maximum amount of N in crop in rice cvars CR1009 (wet season, 1991 - 92) and IR64 (July - October, 1992) at Thanjavur (Experiments 1 and 3).

N loss from crop (Experiments 1, 2 and 3)

In treatments other than T1 in Experiment 1, T2 and T3 in Experiment 2, and T1 in Experiment 3 the $N_{c,max}$ was not maintained until H stage. The negative N_c increment observed during grain filling is interpreted as a loss of N from the crop. In cvar CR1009 a maximum of 25% of $N_{c,max}$ was lost from the crop (Figure 8). Only small amount of N may have been lost in dead roots. The posibility of N loss in the form of sampling losses of dead leaves was minimised by careful sampling of the plants. The loss of N may have occurred by volatilisation of NH_3 during transport of amides, resulting from the breakdown of protein in the leaf and stem, in the phloem vessels under alkaline pH (Morgan and Parton, 1989). The loss in IR64 was not significantly related to $N_{c,max}$.

Loss of N from the crop was positively related to the amount of N present in the leaf mass at F stage. The correlation between leaf N% at $t_{N,max}$ and N loss was less significant, as was also the case for leaf N% at any post-PI stage. This suggests that the loss of N from the crop is more connected to the amount of N available for translocation than to the concentration of N in the leaf itself. Further investigation might confirm the hypothesis that the N loss is related to the N-sink strength represented by spikelet filling, relative to the remobilisation rate of N in the leaf mass.

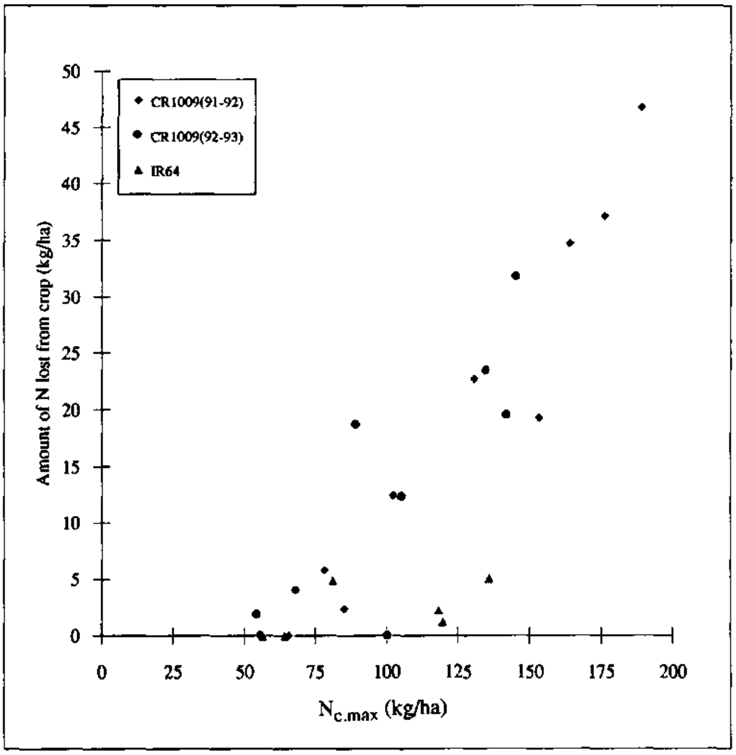
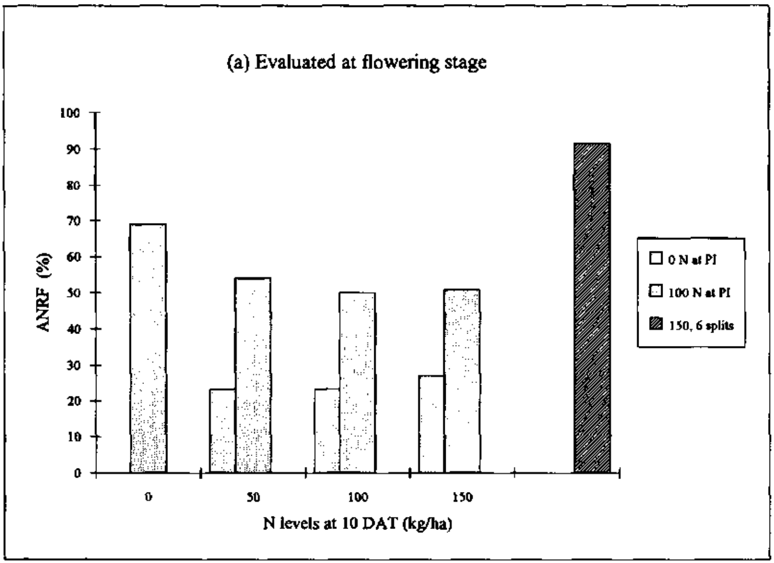


Figure 8. Relationship between amount of N lost from crop and maximum amount of N in crop in rice cvars CR1009 (wet season, 1991 - 92) and IR64 (July - October, 1992) at Thanjavur (Experiments 1 and 3).

Apparent recovery of applied N (Experiments 1, 2 and 3)

Apparent N recovery (ANR) from applied urea N was calculated from the N_c present in excess of the N_c in the control treatments, and was expressed as the percentage of the total amount (i.e. at 10 DAT + at PI) of N applied. We define ANR_F as ANR evaluated at F stage, ANR_H at H stage, and ANR_X at $t_{N,max}$. ANR_F was found to be low (23 to 27%) for the treatments that received 50, 100 and 150 kg N/ha at 10 DAT. ANR_F ranged from 50 to 69% in treatment which received N at PI (Figure 9).


(a) Evaluated at flowering stage

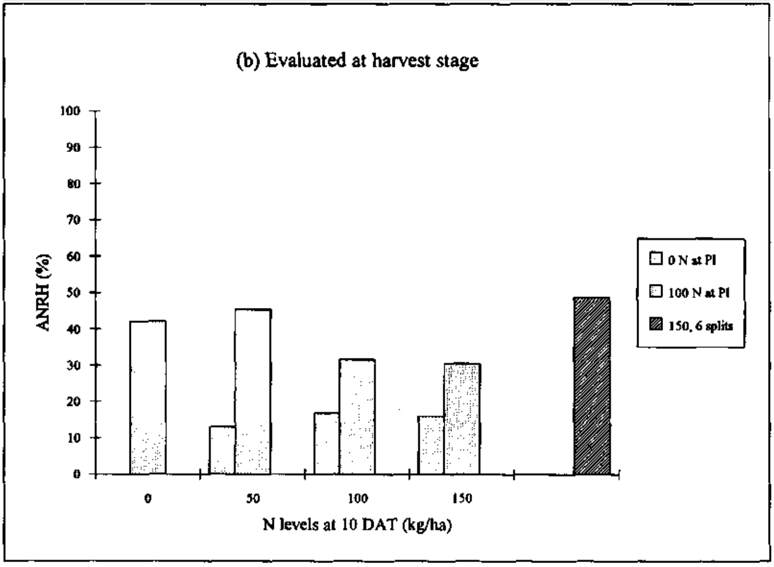

(b) Evaluated at harvest stage

Figure 9. Apparent recovery (as evaluated at F and at H stages) of N applied at 10 DAT and at PI in rice cvar CR1009 during wet season, 1991 - 1992, Thanjavur (Experiment 1).

In Experiments 1 and 2, ANR_X showed a similar pattern as that of ANR_F because $t_{N,max}$ coincided with F stage for most of the treatments. ANR_H ranged from 13 to 17% in the treatments which received N at 10 DAT only. ANR_H ranged from 31 to 45% in the treatments which received additional 100 kg N at PI stage. The first set of treatments (0 N at PI) showed an increased ANR with increase in N application at 10 DAT and the trend was reverse in the second set of treatments (additional 100 kg N at PI). Similar results but of lower magnitude were observed in Experiment 2 (Figure 10).

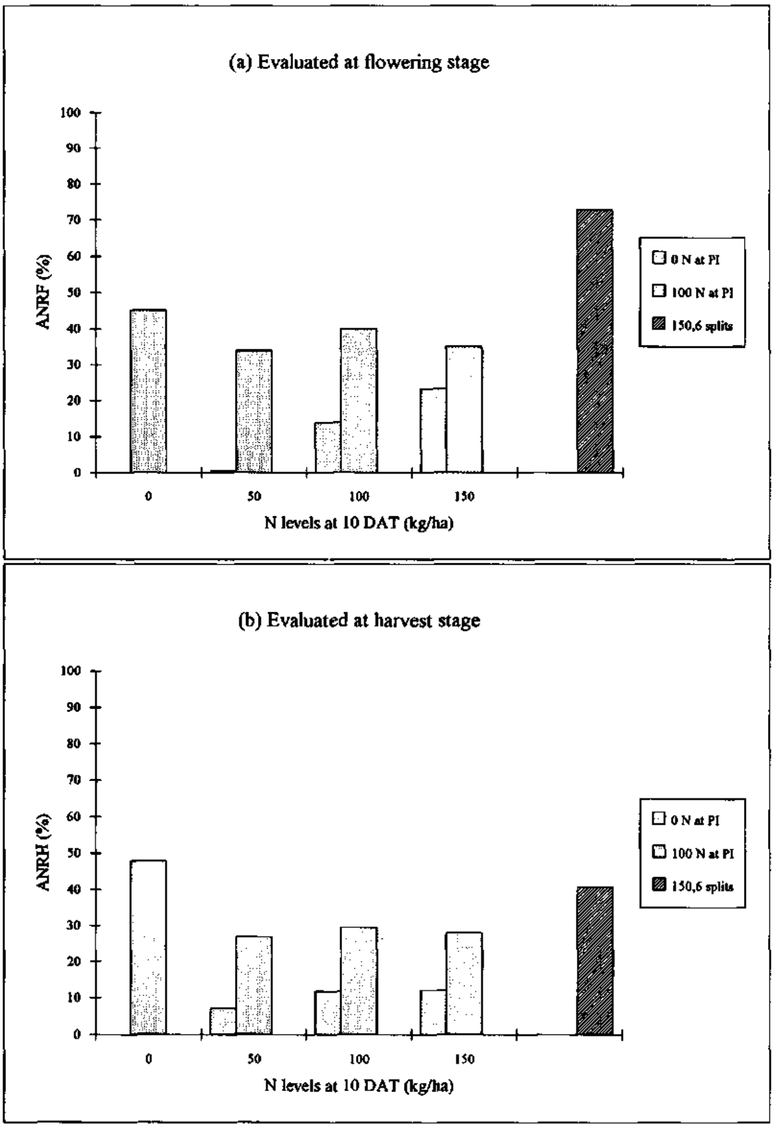
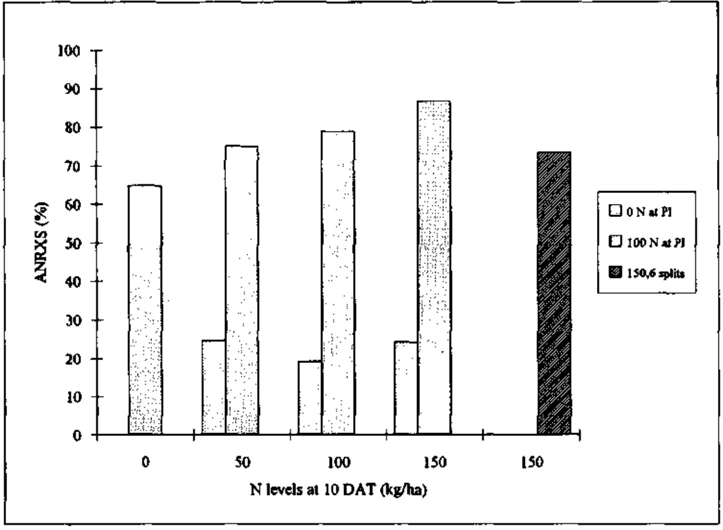


Figure 10. Apparent recovery (as evaluated at F and at H stages) of N applied at 10 DAT and at PI in rice cvar CR1009 during wet season, 1992 - 1993, Thanjavur (Experiment 2).

Apparent recovery for the different splits (ANR_{XS}) was calculated as explained for Table 5. It ranged from 19 to 25% from the N applied at 10 DAT (50, 100, 150 kg/ha) and from 65 to 87% for the 100 kg N applied at PI stage. Contrary to the constancy of recovery reported by de Datta (1986), recovery from N application at PI stage increased with increasing levels of application at 10 DAT. This increase was up to 24 absolute percent points of ANR (Figure 11).

(a) 1991-1992



(b) 1992-1993

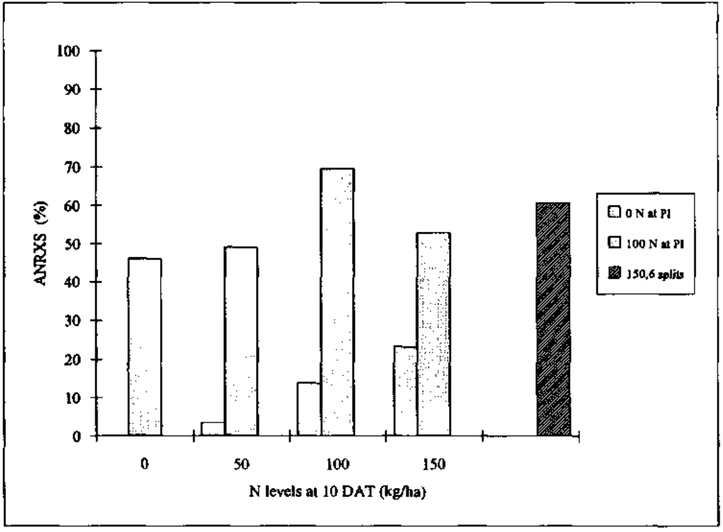


Figure 11. Apparent recovery (as evaluated at $t_{N,max}$) of applied N in rice cvar CR1009 during wet season, 1991 - 1993, Thanjavur (Experiments 1 and 2). Each bar represents the recovery from a particular single split application. See also explanation of Table 5.

The recovery from organic sources was varying widely (Figure 12). The FYM registered only 4% and 6% for ANR_F and ANR_H. Among the organic manures the highest recovery was in GM. The urea N was recovered in higher proportition than the N in organic manures. While there was a considerable difference between ANR_F and ANR_H in urea treatments there was not much difference between these two estimates in organic manures.

Split application registered higher recovery than single dose both under 150 kg N/ha (Experiments 1 and 2) and 125 kg N/ha (Experiment 3) situations. The six equal split application of 150 kg N/ha for CR1009 yielded an ANR_F of 92% during 1991 - 1992 and 73% during 1992 - 1993. ANR_H was only 49 and 41% during 1991 - 92 and 1992 - 93 respectively in this treatment. ANR_H from 4 split application of 125 kg N/ha (T5) to IR64 (50%) was comparable to that of 6 split application of 150 kg N/ha to CR1009. ANR_F for 10 split application of urea was the highest recovery (72%) recorded in Experiment 3. The generally low ANR_H was due to the (i) net loss of N after flowering and (ii) more post-F net N uptake in 0 N than in other treatments.

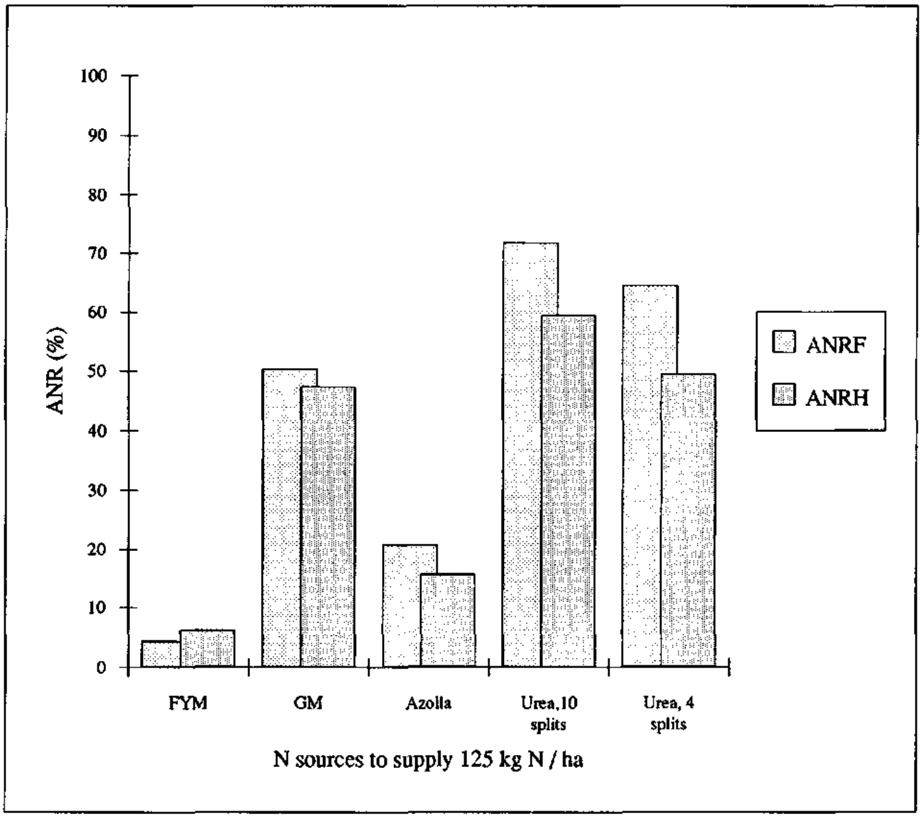


Figure 12. Effect of different sources of N on the apparent recovery of applied N in rice cvar IR64 during wet season, July - October, 1992, Thanjavur (Experiment 3).

N uptake yield and yield attributes (Experiments 1, 2 and 3)

The number of panicles per unit area recorded at H was positively related to N_c at PI, MF, F, H stages and $N_{c,max}$ (Figure 13). However the relation between panicle number at H stage and N_c at PI stage was not significant in Experiments 1 and 2 (CR1009). Based on $N_{c,max}$ values it was observed that cvar IR64 produced as much as 2 to 4 times the number of panicles that was produced in CR1009 (1991 - 1992 & 1992 - 1993) for an unit increase in N_c. Panicle number showed only a weak response to $N_{c,max}$ in Experiment 2. As explained earlier, N uptake stalled during the MT-PI phase. Although N_c could at later stages attain a level similar to those obtained in Experiment 1, the reduction in yield potential suffered during the MT-PI phase could apparently not be repaired by later uptake.

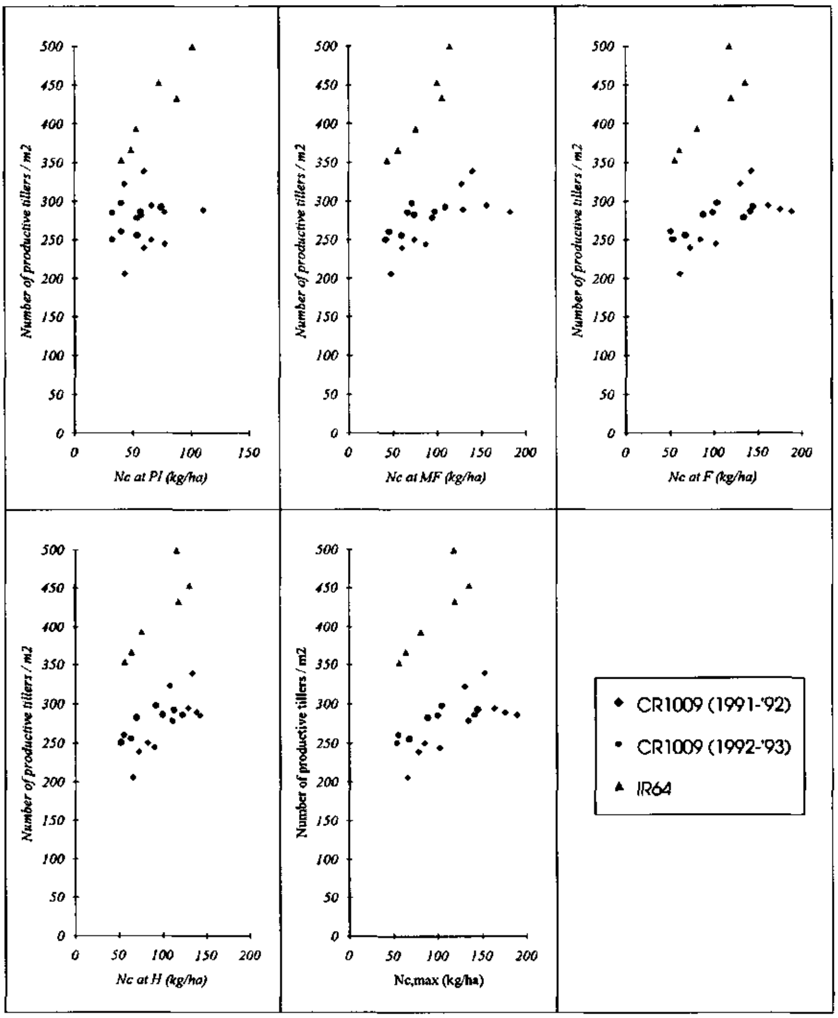


Figure 13. Relationship between amount of crop N at different stages and number of productive tillers in rice cvars CR1009 (wet season, 1991 - 1993) and IR64 (July - October, 1992) at Thanjavur (Experiments 1, 2 and 3).

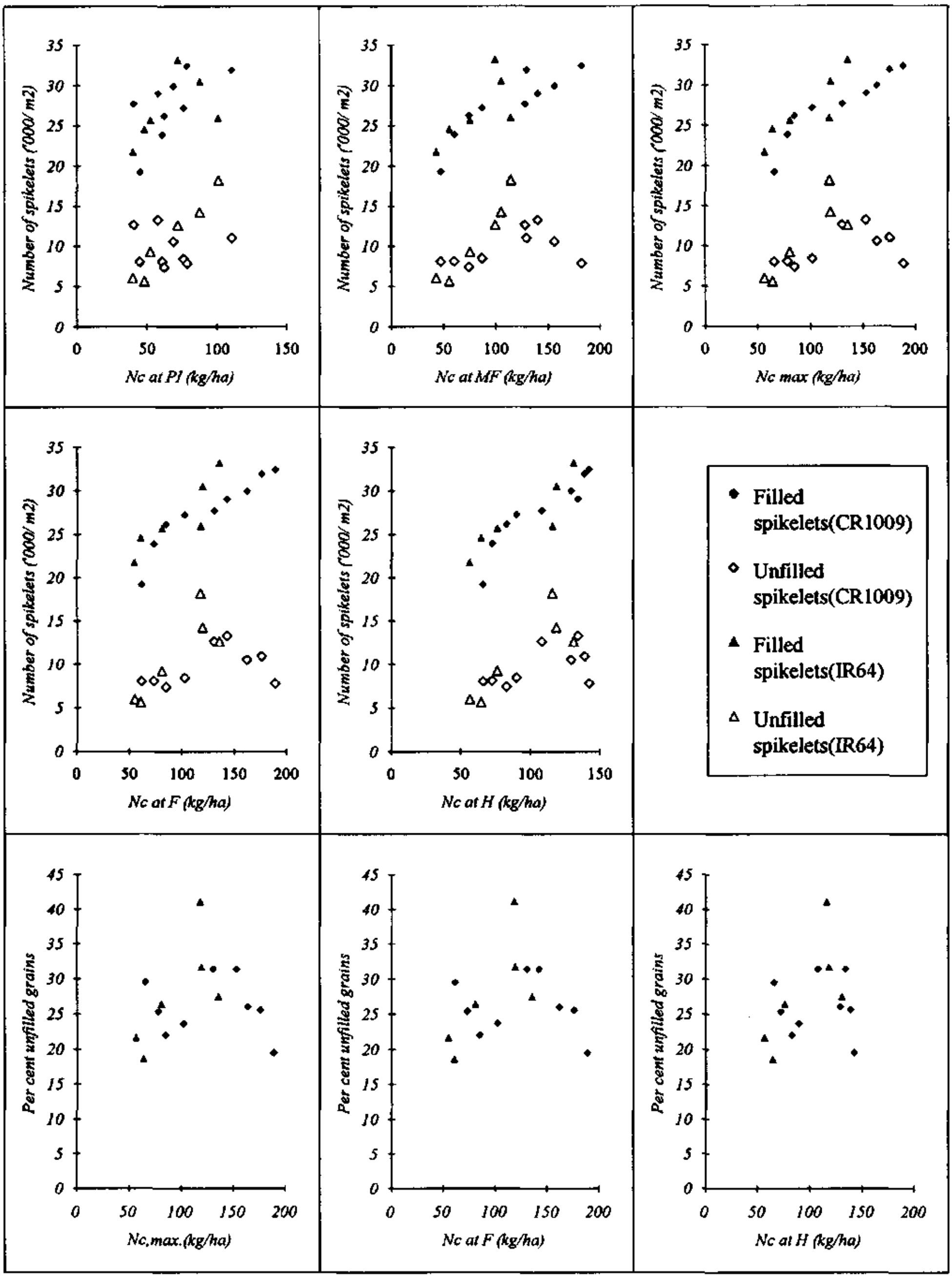


Figure 14. Relationship between amount of N in the crop at different stages and number of spikelets per unit ground surface in rice cvars CR1009 (wet season, 1991 - 1992) and IR64 (July - October, 1992 at Thanjavur (Experiments 1 and 3).

The number of filled spikelets per unit area showed a constant increase with increasing $N_{c,max}$. This was true for unfilled spikelets up to certain level of $N_{c,max}$ values. When the N_c was above 125 kg/ha at MF or F stages, unfilled spikelets showed a decrease with increase in $N_{c,max}$ (Figure 14). IR64 showed slightly higher spikelet number per unit ground surface, at identical N_c values.

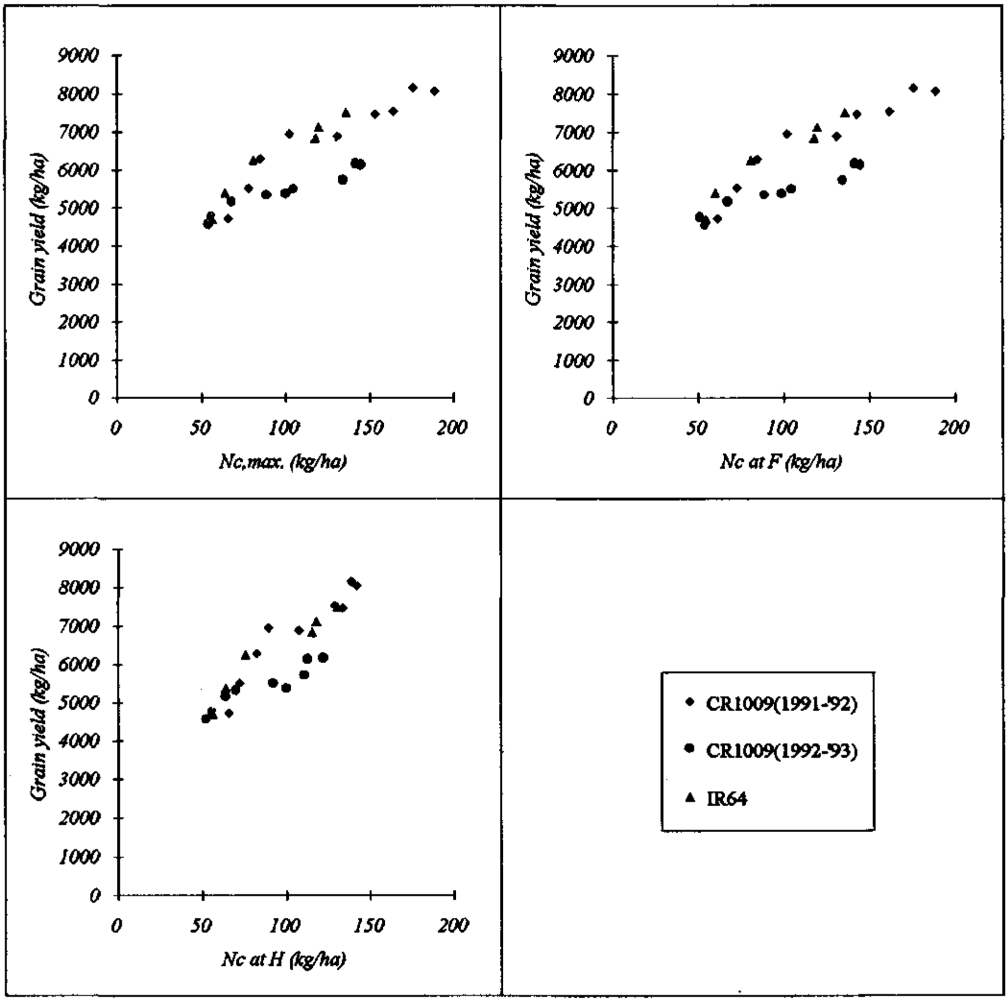


Figure 15. Relationship between amount of N in the crop and grain yield in rice cvars CR1009 (wet season, 1991 - 1993) and IR64 (July - October, 1992) at Thanjavur (Experiments 1, 2 and 3).

Grain yield was positively related to $N_{c,max}$, N_c at F stage and N_c at H (Figure 15). Grain yield per unit amount of $N_{c,max}$ recorded in CR1009 was about the same as in IR64 (Table 6 and 7); however, CR1009 in Experiment 2 recorded a lower efficiency producing certain amount of grain for a given amount of $N_{c,max}$. This reduced efficiency is attributed to the reduced uptake during the MT-PI phase, as explained for panicle number which resulted in reduced spikelet formation. Spikelet number observations, however, were not made in Experiment 2.

Table 6. Effect of graded levels of N application and a high dose of N at PI on $N_{c,max}$ and grain yield in rice cvar CR1009 during wet season, 1991 - 1993, Thanjavur.

Treat	$N_{c,max}$ (kg/ha)		grain yield (kg/ha)	
No.	1991-'92	1992-'93	1991-'92	1992-'93
T1	65.9	54.2	4724	4559
T2	130.8	100.3	6897	5377
T3	78.2	55.9	5525	4750
T4	153.3	105.0	7467	5502
T5	85.1	68.1	6295	5164
T6	163.9	134.7	7537	5725
T7	102.3	89.1	6960	5332
T8	189.0	142.0	8059	6171
T9	176.1	145.2	8159	6144

Table 7. Effect of different sources of N on $N_{c,max}$ and grain yield of rice cvar IR64 during July to October, 1992, Thanjavur.

Treatment	$N_{c.max}$ (kg/ha)	Grain yield (kg/ha)
1. FYM	64.3	5414
2. GM	118.0	6860
3. Azolla	81.1	6279
4. Urea, 10 splits	135.9	7517
5. Urea, 4 splits	119.6	7144
6. No N application	56.5	4729

Summary and conclusions

- Crop N (N_c) content (kg/ha) at any one stage of the crop was linearly related to the amount of N given at 10 DAT.
- In all treatments the maximum value of N_c ($N_{c,max}$) resulting from the application of 100 kg N at PI stage was 2 to 3 times higher than N_c at PI stage in the respective treatments.
- Among the organic sources, GM sustained the highest N_c throughout the season.
- The N uptake from FYM and Azolla was low and this was attributed to the losses of N. In view of the very high NO_3 content in the FYM , it is likely that N losses due to denitrification were high.
- Highest rate of N uptake (6.6 kg/ha/d) from urea was recorded during PI-MF phase in the treatment that received 150 kg N at 10 DAT and 100 kg N at PI stage.
- Among the organic manures, GM treatment registered the highest N uptake rate (3.6 kg/ha/d) during MF-F phase.
- The ratio of N-translocation from leaf to N-translocation from stem was 2 : 1 in IR64 and 2.6 : 1 in CR1009.
- Loss of N from the crop, on an average amounted to 32% of $N_{c,max}$ in Experiments 1 and 2. The N loss in Experiment 3 was not significantly related to $N_{c,max}$.
- Higher values of apparent N recovery (ANR) were obtained when evaluated at F stage than at H stage because a net N gain existed in the 0 N treatment, and a net N loss occured in the other treatments during the post flowering period.
- ANR from 100 kg N/ha applied at PI stage increased with the N-status of the crop (N_c and biomass) at PI stage and the constancy of recovery observed with N applied at 10 DAT failed in this case.
- Split application of urea resulted in higher ANR than single dose applied at 10 DAT.
- Panicle number, filled spikelet number and yield (all per unit area) were positively related to $N_{c,max}$. Unfilled spikelet number showed a positive relation with $N_{c,max}$ up to a $N_{c,max}$ value of 125 kg/ha; beyond this value the trend was reverse.
- Grain yield per unit amount of $N_{c,max}$ recorded in CR1009 was almost the same as in IR64.Yield potential of CR1009 during 1992-1993 was reduced as N uptake stalled during MT-PI phase. The N uptake during the later phases of this crop, although resulting in similar N_c values as obtained in Experiment 1 could not make up for this setback.

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Nitrogen and rice: Influence of nitrogen application levels and strategy on growth, leaf nitrogen content and nitrogen use efficiency

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Abstract

Five field experiments were conducted from 1989 to 1993 at Tamil Nadu Rice Research Institute, Aduthurai and Soil and Water Management Research Institute, Thanjavur, Tamil Nadu, India. The soils at Aduthurai were clayey and in Thanjavur they were sandy loam in texture. Rice varieties ADT 38, CR 1009 and IR 64 were grown under irrigated, transplanted wetland conditions. The treatments consisted of different nitrogen application levels and timings. Observations on biomass and nitrogen content of roots, stems, leaves and panicles, number of tillers, leaves and spikelets and grain and straw yields were recorded. Conclusions were drawn from the results across all the experiments.

There was a linear relationship between total dry matter production and grain yield. Irrespective whether there was N supply or not, the leaf N content was maintained by the crop within an absolute range of 1% by increase in number of leaves per unit ground area. Application of 100 kg N at panicle initiation (higher than normal practice) increased the grain yield through increased number of productive tillers, leaves and filled grains. In these cases the absolute number of unfilled grains was higher when the basal N supply was low. N use efficiency could be increased by supplying more N in the later stages of vegetative phase.

Introduction

Ever since the focus of policy and research was on increasing the per hectare grain yield of rice, nitrogen became the 'star' input both by the farmers and the rice researchers and even after such a historical background, the attention is still sustained. The conclusions from early rice research were mainly empirical in nature (Kirk and Bouldin, 1991). Recently more quantitative descriptions of nitrogen effects on processes that determine rice yields are now forthcoming (Sinclair, 1990; Makarim et al., 1991; Thiyagarajan et al., 1991; ten Berge et al., 1994). It appears that the rice plant has a lot more in store to be unravelled about its adjustment to the environment as Matsushima (1976) pointed out: "the world of rice plants is completely composed of order, rules and regulations and many of them are difficult to comprehend". Rice often surprises us with phenomenal adjustments to its environment - perhaps that is the reason why it has become one of the world's prime food crops.

The quantity of fertilizer N applied to the rice crop by farmers varies with location but there has been a general though cautious increase over time. In Tamil Nadu for example, the amount of fertilizer N recommended two decades ago for the short (105 days) and long (150) duration rice crops was 60 and 75 kg N/ha, respectively, and is now up to 100 and 150 kg/ha.

The rising cost of nitrogenous fertilizers has now reverted research in India back to the topic of exploiting organic nitrogen sources. Although the current study did not explicitly include organic N sources, its direct aim was to increase our understanding of crop response to nitrogen in relation to the environment, with a long term view on designing proper management strategies for a given cropping system which may include organic N sources as well.

In the collaborative research program reported in this volume, three types of common experiments (referred to as CE-I, CE-II, CE-III) were executed to evaluate rice response to N at various experiment stations of national agricultural research centres. All three were conducted at two research stations of Tamil Nadu Agricultural University, Tamil Nadu, India. This paper describes the experiments conducted and some overall conclusions from the data collected.

Materials and methods

A total of five field experiments were conducted. CE-I, CE-II and CE-III were conducted at the experiment station of Tamil Nadu Rice Research Institute, Aduthurai during 1989 - 1990, 1991 - 1992 and 1992 - 1993, respectively, and the CE-II was conducted at Soil and Water Management Research Institute, Thanjavur, Tamil Nadu during 1991 - 1992 and 1992 - 1993. The soils at Aduthurai were clayey Typic Chromusterts and those at Thanjavur were sandy loam Typic Haplustalfs. The details of the field experiments are furnished in the Tables 1 and 2.

Nitrogen was applied as prilled urea by surface broadcasting. When applied at transplanting, N was incorporated by harrowing. Topdressings were not incorporated except at Thanjavur in both CE-II experiments, where urea was incorporated by hand after each split application.

Table 1. General details of five experiments on N management conducted at Aduthurai (ADT) and Thanjavur (TNJ), Tamil Nadu, India. (Treatment details are given in Table 2.)

Details	Common Experiment	Common Experiment II			Common Experiment
	I	TNJ 1	TNJ 2	ADT	III
	89 - 90	91 - 92	92 - 93	91 - 92	1992
No of treatments	4	9	9	9	9
Replications	4	3	3	3	3
Design	RBD	RBD	RBD	RBD	RBD
Variety	ADT38	CR1009	CR1009	CR1009	IR64
Spacing (cm)	20*10	20*10	20*10	20*10	15*10
Seedlings/hill	1	1	1	1	1
Seedling age at planting	34	31	30	32	25
Date of planting	25-10-89	12-09-91	11-09-92	13-07-92	09-09-92
Date of PI (DAT)	38	59	69	70	32
Date of flowering (DAT)	58	91	94	95	58
Date of harvest	31-01-90	11-01-92	08-01-93	09-01-92	21-10-92

Table 2. Treatment details of Common Experiments as conducted at Aduthurai and Thanjavur.

Common experiment I (conducted once)

No.	N applied (kg N/ha)				
	0	21	38	58	Total
	days after transplanting				
T1	0	0	0	0	0
T2	20	10	10	10	50
T3	40	20	20	20	100
T4	60	30	30	30	150

Table 2 continued next page

Table 2 continued

Common Experiment II (conducted three times)

No.	N applied (kg/ha)		
	10 DAT	PI	Total
T1	0	0	0
T2	0	100	100
T3	50	0	50
T4	50	100	150
T5	100	0	100
T6	100	100	200
T7	150	0	150
T8	150	100	250
	150 kg N in six equal splits: at TP, 10 DAT, AT, MT, PI and F		

Common experiment III (conducted once)

No.	N application (kg/ha)							
	0	8	16	24	32	43	58	Total
	Days after transplanting							
T1	0	0	0	0	0	0	0	0
T2	0	0	0	0	0	0	200	200
T3	0	0	0	0	0	100	100	200
T4	0	0	0	0	66.6	66.6	66.7	200
T5	0	0	0	50	50	50	50	200
T6	0	0	40	40	40	40	40	200
T7	0	33.3	33.3	33.3	33.3	33.4	33.4	200
T8	28.6	28.6	28.6	28.6	28.6	28.6	28.6	200
T9	50	25	0	25	0	0	25	125

In all the experiments, plant samples were collected at regular time intervals from the time of transplanting to harvest. The roots, stem plus sheaths, leaves and panicles were separated, dried at 80 ºC and the dry weights were recorded to calculate the biomass. Subsamples were drawn to determine the N content of the plant organs. The number of tillers, leaves , panicles and grains were counted from the same samples. The final grain and straw yields were also recorded and the benefit/cost ratio was worked out.

Results and discussion

Effects of applied N on dry matter production and grain yield

The total dry matter produced increased in general with increasing level of N application only up to 150 kg N/ha. Beyond 150 kg there was a plateau (Figure 1). It could be observed that for the same N application level the dry matter produced differed considerably over the various experiments. This could be due to the environmental factors like soil and weather and also to differences in varietal characteristics. However, the results from all the experiments showed (Figure 2) that there was a significant linear relationship between total dry matter (TDM, t/ha, including roots) produced and grain yield Y (t/ha) with a correlation coefficient (r) of 0.98. The relationship is expressed as,

$$Y = 0.975 + 0.377 * TDM$$

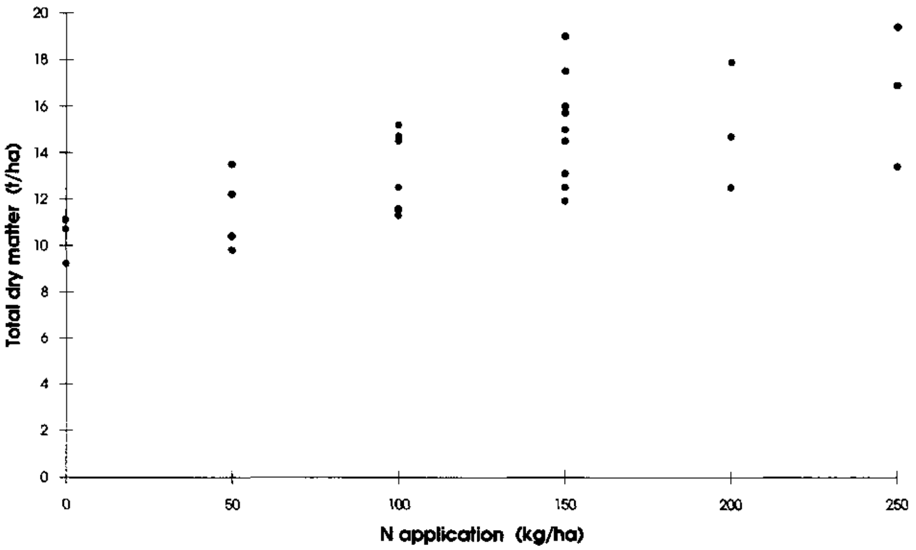

Figure 1. Effect of N application (total N applied) on dry matter production in Common Experiments I and II (four experiments) during 1989 - 1993 in Aduthurai and Thanjavur. (Treatment details in Table 2.)

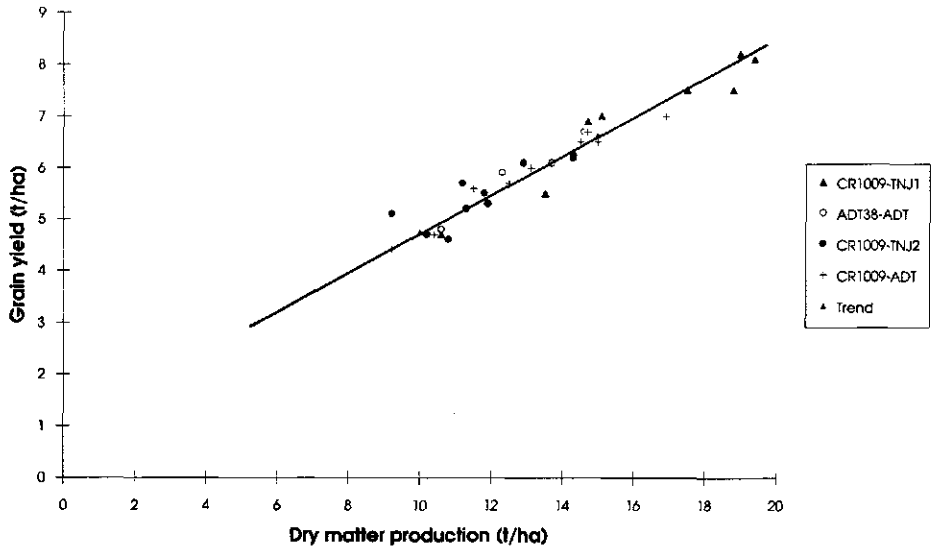

Figure 2. Relationship between grain yield and total dry matter produced under different N application levels in four experiments conducted during 1989 - 1993 in Aduthurai and Thanjavur. The line represents the regression equation mentioned in the text. (For legend see Table 1. Treatment details in Table 2.)

Table 3. Effect of N application on yield characterisics, harvest index (kg grain/kg above-ground dry matter) and N use efficiency (kg grain/kg N applied). Common Experiment I, Aduthurai, 1989-1990, rice cvar ADT38.

N applied kg/ha	panicles (t/ha)	grains (t/ha)	straw* (t/ha)	harvest index	N use efficiency (kg/kg)
0	5.6	4.8	4.2	0.49	-
50	6.6	5.9	4.9	0.51	22.0
100	6.9	6.1	6.0	0.47	13.0
150	7.4	6.7	6.4	0.49	12.7

* roots not included

When the normal N application practice was followed - as in CE-I; and for the graded N doses applied on 10 DAT in CE-II - yield generally increased with the amount of N applied (Tables 3, 4).

In CE-II, 100 kg N was supplied at PI to crops which received graded doses of N at 10 DAT (0, 50, 100 and 150 kg/ha). There was also a treatment with 150 kg N/ha applied in 6 equal splits at 0, 10, 25, 40, 65 (PI) and 90 (flowering) DAT which is the normal recommended practice for the variety. Application of 100 kg N at PI increased the grain yield in all the basal N supply situations, but the magnitude of yield differences varied with location and year (Table 4). The grain yields obtained at Thanjavur in 1992 - 1993 and at Aduthurai in 1991 - 1992 were lower than those obtained at Thanjavur in 1991 - 1992, due to reduced N uptake (Sivasamy et al., this volume).

The overall picture (Figure 3) indicated that application of 100 kg N at PI to a crop which was in short supply of N promotes grain yield. This is of particular importance in situations where the farmers are not able to apply enough nitrogen in the early stages of the crop (before PI) due to constraints related to limited availability of irrigation water, labour (weeding prior to N application), and financial resources to acquire fertilizers. The harvest index (grain yield/total aboveground biomass) in all the three experiments ranged from 0.48 to 0.50.

Table 4. Effect of N application on grain yield and harvest index (kg grain/kg above-ground dry matter), in three experiments (Common Experiment II) conducted during 1991 - 1993 at Thanjavur (TNJ) and Aduthurai (ADT), rice cvar CR1009. See also Tables 1, 2.

No.	grain yield (t/ha)				harvest index
	TNJ 1 91 - 92	TNJ 2 92 - 93	ADT 91 - 92	mean	mean
T1	4.7	4.7	4.4	4.6	0.50
T2	6.9	5.1	5.6	5.9	0.48
T3	5.5	4.6	4.7	4.9	0.50
T4	7.5	5.5	6.0	6.3	0.50
T5	6.3	5.2	5.7	5.7	0.50
T6	7.5	5.7	6.7	6.6	0.49
T7	7.0	5.3	6.5	6.3	0.50
T8	8.1	6.2	7.0	7.1	0.50
T9	8.2	6.1	6.5	6.9	0.49

The highest grain yields in Common Experiment II were obtained for the 150 + 100 N and 150 (6 splits) N treatments, both at Thanjavur and at Aduthurai. The soils being coarse in texture in Thanjavur, the same yields were attained in Treatment 9 where only 150 kg N was applied, but in a higher number of splits. This increased the fertilizer N recovery (Sivasamy et al., this volume).

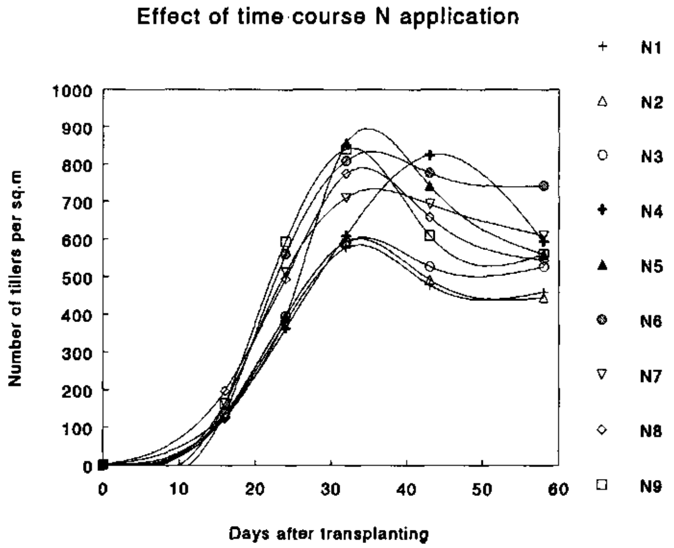

Figure 3. Effect of N application on the time course of tiller number, until flowering. Aduthurai, 1992, rice cvar IR 64. (Treatment details in Table 2.)

Table 5. Grain yield and N use efficiency in Common Experiment III, Aduthurai, 1992, rice cvar IR64.

No.	first dressing DAT	last dressing DAT	total N (kg/ha)	grain yield (t/ha)	N use efficiency (kg/kg)
T1	-	-	0	4.5	-
T2	58	58	200	4.3	-1.0
T3	43	58	200	5.4	4.5
T4	32	58	200	5.9	7.0
T5	24	58	200	6.3	9.0
T6	16	58	200	6.6	10.5
T7	8	58	200	6.2	8.5
T8	0	58	200	5.8	6.5
T9	0	58	125	5.6	5.5

In the CE-III, application of 200 kg N/ha in 5 splits commencing from 16 DAT resulted in the highest grain yield and N use efficiency (Table 5). Almost identical yields were obtained for the same total N level when application started on 8 DAT (6 splits) and 24 DAT (4 splits). The yield decreased if N application was delayed further. When the full dose of 200 kg N was applied at flowering there was even a negative influence as compared to the control treatment T1.

N use efficiency

In CE-I, the N use efficiency - expressed here as grain yield (kg/ha) per unit of N applied (kg/ha) - was highest (22 kg/kg) for 50 kg N/ha. When more N was applied, efficiency decreased dramatically (Table 3). Application of 150 kg N/ha in six splits (normal recommended practice) gave the highest N use efficiency in CE-II (Table 6). When N was applied as a single dose at 10 DAT, treatments which received 100 and 150 kg N/ha showed a higher N use efficiency than when 50 kg N/ha was given (Table 6). The maximum overall N use efficiency was obtained for N application levels of 50, 100 and 150 kg/ha. For the same application levels, N use efficiency varied with application scheme, indicating the importance of adopting proper N application strategy.

The N use efficiency can also be evaluated on a 'per split' basis by assessing the yield increment resulting from an increment in the amount of N applied. For the 100 kg N applied at PI, N use efficiency was highest when no N was applied before PI; it decreased with increasing pre PI N application level (Table 7).

Table 6. Overall N use efficiency (kg grain/kg N applied in total) in three experiments (Common Experiment II) conducted during 1991 - 1993 at Thanjavur (TNJ) and Aduthurai (ADT), rice cvar CR1009.

No.	N use efficiency (kg/kg)			
	TNJ 1 91 - 92	TNJ 2 91 - 92	ADT 92 - 93	mean
T1	-	-	-	-
T2	22.0	8.0	12.0	14.0
T3	16.0	4.0	6.0	8.6
T4	18.7	6.0	10.7	11.7
T5	16.0	6.0	13.0	11.6
T6	14.0	5.5	11.5	10.3
T7	15.3	4.7	14.0	11.3
T8	13.6	6.4	10.4	10.1
T9	23.3	10.0	14.0	15.7

Table 7. N use efficiency (increase in grain yield per kg N applied) for N applied at 10 DAT (columns 2-4) and for 100 kg N applied at PI (columns 5-7) in three experiments (Common Experiment II), conducted during 1991 - 1993 at Thanjavur (TNJ) and Aduthurai (ADT), rice cvar CR1009.

No.	TNJ 1 91 - 92	TNJ 2 91 - 92	ADT 92 - 93	TNJ 1 91 - 92	TNJ 2 91 - 92	ADT 92 - 93
T1	-	-	-	-	-	-
T2	-	-	-	22.0	8.0	12.0
T3	16.0	4.0	6.0	-	-	-
T4	-	-	-	20.0	7.0	13.0
T5	16.0	6.0	13.0	-	-	-
T6	-	-	-	12.0	5.0	10.0
T7	15.3	4.7	14.0	-	-	-
T8	-	-	-	11.0	9.0	5.0

The results of CE-III (Table 5) show that delaying the N application (T4-T7) increased N use efficiency. (Normally, 2/5 of total recommended N is applied as basal and the rest is applied in 2 or 3 splits up until flowering, in short duration cvars such as IR64). In CE-II, delayed application resulted in higher N use efficiency for the light textured Thanjavur soil, but not for Aduthurai. A possible explanation is that the heavy soil at Aduthurai had a higher capacity to retain applied N. In all CE-II cases, N application in six equal splits gave the best N use efficiency. In long duration varieties such as CR1009, an even supply of N throughout the season seems to be more important than in short duration varieties.

Impact of delayed N application on tillering

The positive effects of delayed N application on grain yields were due to the marked effects on the tiller production and grain filling. The results from the CE-III with variety IR 64 showed that the tiller number increased when N application was delayed (Figure 3). If the delay was beyond PI (Treatment T3) the positive effect seen in T6 was not observed; tillers were only sustained longer as a result of N application. The difference between maximum tiller number and the number of tillers recorded at flowering was highest in T4, T5 and T9. The beneficial effect of commencing N application at 16 DAT was that more tillers were sustained upto flowering, which resulted in higher yields.

The increase in tiller number due to N application at PI was also noticed in CE-II. The data from the 1991 - 1992 experiment at Thanjavur show a marked increase in the number of productive tillers due to 100 kg N application at PI (Table 9). In Treatments T2 (0 + 100 kg N) and T4 (50 + 100 N), the number of productive tillers was higher than in the highest yielding treatment, T8 (150 + 100 kg N). The effect of N application at PI on the number of leaves produced was also significant.

Table 8. Minimum and maximum values of overall N use efficiency for selected levels of total N application, as observed across five experiments conducted in Aduthurai and Thanjavur, Tamil Nadu, 1989 - 1993. Rice cvars CR1009, ADT38 and IR64.

Total N applied	N use efficiency (kg/kg)	
(kg/ha)	minimum	maximum
50	4	22
100	6	22
150	5	23
200	5	14
250	6	14

Table 9. Number of productive tillers, filled grains, and grain yield in Common Experiment II at Thanjavur (TNJ), 1991 - 1992, rice cvar CR1009.

Treatment	productive tillers per m^2	filled grains per m^2	unfilled grains (%)	grain yield (kg/ha)
T1	206	19201	29.4	4724
T2	322	27675	31.3	6897
T3	239	23850	25.4	5525
T4	339	29039	31.3	7467
T5	250	26162	22.0	6295
T6	294	29940	26.0	7537
T7	244	27218	23.6	6960
T8	286	32443	19.4	8059
T9	289	31917	25.6	8159

Table 10. Leaf N content at different development stages, as a function of total fertilizer N applied in Common Experiment III. (Rice cvar IR 64, Aduthurai, 1992)

DAT	development stage	range of N applied (kg/ha)	range of leaf N content (%)
16	Tillering	0 - 75	3.68 - 4.33
24		0 - 86	2.81 - 3.32
32	P.I.	0 - 114	2.52 - 3.32
43		0 - 143	1.66 - 2.60
58	Flowering	0 - 172	1.39 - 2.45

Impact of delayed N application on grain filling

Application of 100 kg N at PI also increased the total number of filled grains (Table 9). The magnitude of increase was higher when the N applied at 10 DAT was lower. The number of filled grains in treatments T6 and T8 were higher than in T2 and T4, and accounted for the higher yields observed in T6 and T8.

The higher percentage unfilled grains in T2 and T4 vs T6 and T8 suggests that carbohydrate source limitation during grain filling was associated with lower basal N applications, as applications at PI were the same in these treatments. The highest yielding treatment T9 also had 25.5% of unfilled grains, suggesting that the yield could still be increased by elevating the source strength.

Adjustment of leaf number and leaf N content

It appears that the rice crop adjusts the number of leaves per unit ground area as N uptake increases, resulting in a confined range of leaf N contents during the pre-PI stage. The data from the CE-II and CE-III show that, irrespective of N supply, the leaf N content remained within an absolute range of 1% (Table 10).

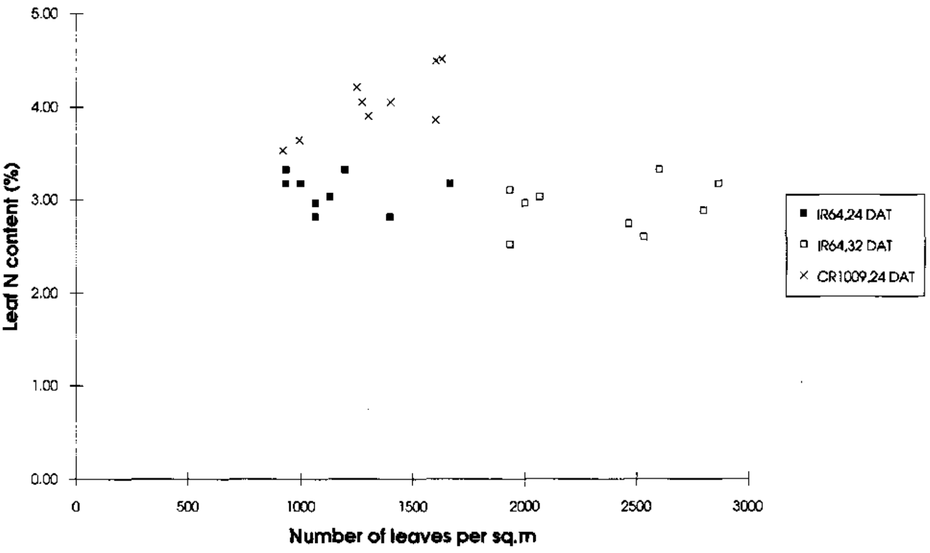

Figure 4. Relationship between number of leaves per m^2 and leaf N content at vegetative growth stages of rice cvars CR1009 (Thanjavur, 1991 - 1992) and IR64 (Aduthurai, 1992), for different N application levels. (Treatment details in Table 2).

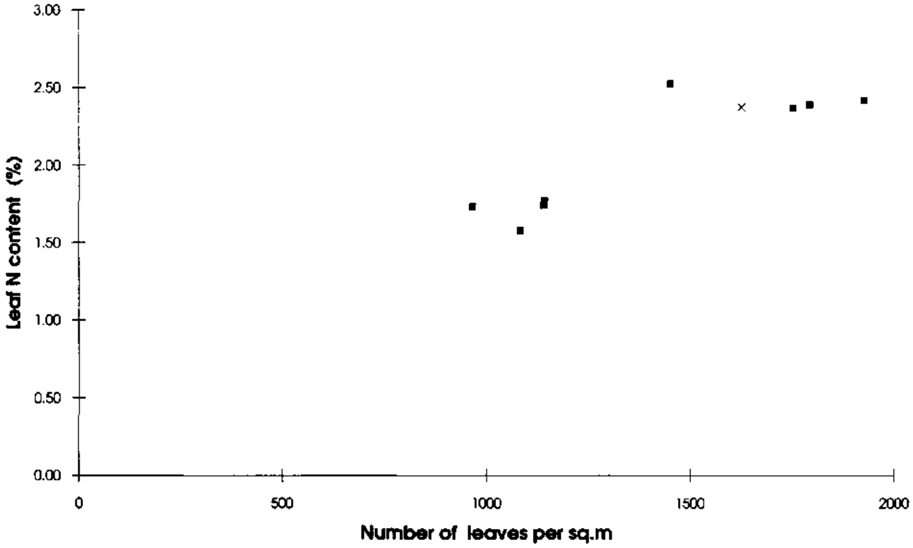

Figure 5. Relationship between number of leaves per m^2 and leaf N content after 100 kg N application at PI, in rice cvar CR1009 at Thanjavur, 1991 - 1992.

Higher N supply resulted in more leaves maintaining the same range in N%. The range of N content in the leaves in relation to the number of leaves appeared to depend upon the physiological stage of the crop. At the beginning of tillering stage, the N content ranged from 3.5 to 4.5% (Figure 4) and from then on until flowering it ranged from 1.5 to 2.5% (Figure 5). This phenomenon was also observed in CE-II, where the number of leaves as well as leaf N content increased due to 100 kg N application at PI, but still the N content range remained within 1% in comparison with treatments which did not receive N at PI. This was confirmed by CE-III where, until PI stage, the leaf N content remained between 1.5 to 2.5% (Figure 4), though the amount of N applied ranged from 0 to 114 kg/ha. Thus, the number of leaves produced in rice is sensitive to N supply, in contrast to the behaviour of non tillering crops (Sinclair, 1990).

Conclusions

In all our experiments, a linear relationship was found between dry matter production and grain yield in rice. Variations in timing of N supply and varietal differences resulted in differences in dry matter production. Increased N uptake leads to a higher number of leaves per unit ground area, and only marginally increases leaf N content. The latter, however, depends mostly on the physiological stage of the crop. When N supply to rice crop was delayed until 16 DAT, higher yields were obtained. These were associated with increased tiller production and leaf N content.

Application of 100 kg N/ha at PI to a crop which received graded doses of N at 10 DAT, increased the grain yield. This was associated with an increased number of tillers, leaves and filled grains, and with an increased leaf N content. Application of 100 kg N/ha at PI leads to higher percentage of unfilled spikelets in a crop which received low N supply basally. This is attributed to a lack of biomass formed before PI.

Delaying the first N application until 16 DAT increased overall N use efficiency (kg grain/kg N applied). Further delay decreased efficiency, but values were still higher than under recommended practice, except when the first application was delayed beyond PI.

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Nitrogen requirement of irrigated rice at different growth stages

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Abstract

A field experiment on N requirement of irrigated rice (cv. IR64) was conducted at Ciwalen, Indonesia, during the 1992 dry season. The experiment consisted of 12 fertilizer treatments ranging from 0 to 600 kg urea/ha in different splits. Nitrogen application during tiller formation stage (12 DAT) and at panicle initiation stage (48 DAT) was most effective in increasing N uptake and grain yield. Late N application (at 60 or 72 DAT) delayed harvest and increased N uptake and grain yield, mainly through an increase in the number of productive tillers per hill. The zero-N yield was relatively high (4 t/ha) because of a good soil N supplying capacity. Largest yield was obtained if 600 kg urea/ha was applied in 6 equal splits, from 12 DAT onwards or if the first N application was postponed up to panicle initiation (6.9 t/ha). Yields increased linearly with total N-uptake at harvest, and did not level off. Timing and level of nitrogen fertilization also affected tiller production. For a 12 day period within the vegetative stage, the tiller number did not increase or even decreased if the N concentration in stem and leaves dropped below 1.9%.

Introduction

The yield potential of irrigated rice is determined by solar radiation and temperature, provided no nutrient limitations or pests and diseases occur. Solar radiation during the reproductive and ripening stages is usually positively related to yield. Higher temperatures tend to accelerate rice growth and may shorten the duration of the grain filling period, thus negatively affecting yield (Oldeman, et al., 1987). The yield level obtained in the field is usually far below its potential because of nitrogen deficiency. The method of N application strongly affects rice yield. Optimum plant-N requirements may differ between dry and wet seasons. Akita et al. (1987) indicated that in the dry season, solar radiation usually increases from transplanting to harvest. Yields are therefore often not limited by solar radiation levels during the ripening stage. Yields in the dry season can be increased by improving the number of spikelets produced per unit of absorbed N. In the wet season, low solar radiation levels and poor N status of the crop may limit rice yield. Mimoto, cited in Akita et al. (1987) showed that, with late deep placement fertilization, yield increases of "panicle weight" type varieties which have fewer panicles per m^2 were higher than increases of "panicle number" varieties which have more panicles per m^2. Postponement of N fertilizer application up to mid-tillering or panicle initiation may not affect yield if the soil N supplying capacity is sufficiently large. In this study a field experiment was conducted to investigate the N uptake capacity of irrigated lowland rice at different growth stages and to match fertilizer application accordingly.

Materials and Methods

A field experiment to determine the N uptake capacity of irrigated rice was conducted at Ciwalen, Cipanas, West Java, Indonesia (107°01'E, 6°45'S, 1138 m asl) during the 1992 dry season. The soil is classified according to Soil Taxonomy (Soil Survey Staff, 1975) as a Haplorthox. IR64 was grown in puddled soil under fully irrigated conditions from 28 July to 24 November 1992, using 21 days old seedlings and a plant spacing of 20 cm x 20 cm. Treatments comprised timing and rate of urea N-fertilizer (46% N). Total amount of nitrogen applied ranged from 0 to 600 kg urea / ha and the number of splits from 0 to 7 (Table 1). Treatments were arranged in a complete randomized block design with three replications. The experimental plot size was 4 m x 5 m. These plots remained flooded throughout the experiment. P and K were applied basally at a rate of 60 kg/ha. During the experiment occasional spraying against pests and diseases was needed. At 12, 24, 36, 48, 60 and 72 days after transplanting (DAT) two hills per plot were sampled to determine dry weight and N concentration of plant organs (excluding roots) and tiller number. At harvest, straw weight and yield (6 m^2 harvest area) and yield components (6 hills per plot) were determined. A multiple regression analysis was used to relate N uptake and grain yield at harvest to the amount of N applied at different days after transplanting:

$$Y = b_0 + b_1A_0 + b_2A_{12} + b_3A_{24} + b_4A_{36} + b_5A_{48} + b_6A_{60} + b_7A_{72}$$

where:

Y = grain yield or N uptake at harvest
A_i = level applied at i DAT (kg urea/ha)
b_j = regression coefficient j

A simple linear regression was performed to relate grain yield to N uptake at harvest. The crop growth simulation model MACROS-L1D (Penning de Vries et al., 1987) was used to simulate potential crop growth for the 1992 dry season, assuming that growth was not limited by other factors than solar radiation and temperature. Weather data were collected at a meteorological station, located within 3 km of the experimental field. Simulated and observed values of total dry matter of stems and leaves and final grain yield were compared.

Table 1. Overview of timing and rate of N application for the various treatments in the field experiment. (Cv. IR64, dry season 1992, Ciwalen).

Treat-ment	Time of urea application (DAT) kg ha^{-1}							
	0	12	24	36	48	60	72	Total
T1	0	0	0	0	0	0	0	0
T2	0	0	0	0	0	0	600	600
T3	0	0	0	0	0	300	300	600
T4	0	0	0	0	200	200	200	600
T5	0	0	0	100	100	100	100	600
T6	0	0	150	150	150	150	150	600
T7	0	120	120	120	120	120	120	600
T8	85.7	85.7	85.7	85.7	85.7	85.7	85.7	600
T9	70	70	70	70	70	70	70	490
T10	50	50	50	50	50	50	50	350
T11	30	30	30	30	30	30	30	210
T12	150	150	150	150	0	0	0	600

Table 2. Dates of phenological events for each treatment in the field experiment. (Cv. IR64, dry season 1992, Ciwalen).

Treat-ment	Date of heading (DAT)	Date of harvest (DAT)
T1	67	105
T2	66	116
T3	66	119
T4	66	113
T5	70	112
T6	66	110
T7	66	110
T8	66	109
T9	70	109
T10	68	106
T11	68	105
T12	67	109

Results and Discussion

Heading and harvest dates for each treatment are summarized in Table 2. Application of fertilizer delayed harvest by a maximum of two weeks (T2, T3).

Dry weights of plant organs

Dry weights of plant organs for the various treatments are given in Table 3. Grain yields (0% moisture) ranged from 3.5 t/ha for T1 to 6.3 t/ha for T4. Straw weight decreased from 72 DAT to harvest, indicating a translocation of carbohydrates from the stem to the grains. The MACROS-L1D simulation model was used to simulate dry matter (straw and grain) production. Simulations were compared with observed data for T8. Simulations and observations agreed well up to 48 DAT. However, at 60 and 72 DAT, simulated values were lower than observed values. The simulated crop growth duration was much longer than the actual crop growth duration due to erroneous values for crop development rate. Simulated rice yield was 6.7 t/ha, which is close to the maximum observed rice yield (Table 3). The discrepancy between simulated and observed biomass indicates that biomass production was not satisfactory predicted by the MACROS-L1D model. Future work will involve testing of an improved version of MACROS-L1D, ORYZA1 (Kropff et al., 1993) which takes into account the effect of leaf N on assimilation rate and calculates leaf area in a manner different from MACROS-L1D.

Table 3. Dry weight of plant organs (kg/ha) at different growth stages per treatment in the field experiment. (Cv. IR64, dry season 1992, Ciwalen). Grain yield is corrected for 0% moisture.

Treatment	Plant (stem + leaves)							Panicle	Straw	Grain
	0 DAT	12 DAT	24 DAT	36 DAT	48 DAT	60 DAT	72 DAT	72 DAT	harvest	harvest
T1	6	84	491	1416	2838	4238	6367	895	3735	3494
T2	6	85	389	1491	2891	4100	8513	650	6213	4304
T3	6	70	375	1379	2984	4254	6469	779	5973	5142
T4	6	84	453	1466	3454	6250	7546	611	7503	6345
T5	6	81	471	1550	3871	5925	8633	411	7492	6175
T6	6	80	408	1241	3338	5842	8521	517	6740	5972
T7	6	94	509	1950	3350	6925	9167	881	7356	6223
T8	6	88	581	1721	4184	8213	10713	533	8104	5754
T9	6	104	638	2063	4241	7579	8925	523	7153	5419
T10	6	108	551	1588	3588	6463	8502	1164	5610	4779
T11	6	79	460	1704	3091	5754	7767	893	5406	4171
T12	6	126	885	2606	5009	8125	10750	768	7789	5135

Table 4. Nitrogen content in plant organs (%) at different growth stages per treatment in the field experiment. (Cv. IR64, dry season 1992, Ciwalen).

Treat-ment	Straw 0 DAT	Straw 12 DAT	Straw 24 DAT	Straw 36 DAT	Straw 48 DAT	Straw 60 DAT	Straw 72 DAT	Panicle 72 DAT	Straw harvest	Grain harvest
T1	2.58	3.47	2.77	2.47	1.77	1.17	1.23	1.37	0.74	1.06
T2	2.58	3.66	2.67	2.53	1.87	1.37	1.15	1.22	1.11	1.50
T3	2.58	3.57	2.77	2.31	1.64	1.32	1.91	1.55	1.09	1.39
T4	2.58	3.51	2.76	2.55	1.42	2.24	2.11	1.57	1.34	1.68
T5	2.58	3.55	2.69	2.36	1.54	2.09	2.07	1.51	1.00	1.60
T6	2.58	3.31	2.81	2.56	1.66	1.92	1.89	1.54	1.06	1.47
T7	2.58	3.85	3.04	2.6	1.89	1.99	1.59	1.29	1.08	1.63
T8	2.58	3.71	2.97	2.81	1.84	1.95	1.67	1.33	0.95	1.48
T9	2.58	3.63	3.24	2.62	1.85	1.82	1.59	1.37	0.98	1.48
T10	2.58	3.2	3.1	2.7	1.77	1.75	1.53	1.42	0.80	1.39
T11	2.58	3.8	3.29	2.38	1.63	1.55	1.49	1.22	0.78	1.25
T12	2.58	3.9	3.23	2.83	1.52	1.84	1.63	1.38	0.90	1.34

N concentrations in plant organs

The plant N concentrations measured for each treatment are summarized in Table 4. The maximum N concentration of the rice plant tissue throughout the growth cycle was determined by selecting the highest plant N concentrations across all treatments per sampling date. The resulting envelope curves are shown in Figure 1. Plant N concentration increased from transplanting up to 12 DAT, then decreased up to 48 DAT (panicle initiation stage). After that time, N concentration slightly increased, then continuously decreased up to harvest. The maximum N concentration of the rice plant (straw and panicle) at 0, 12, 24, 36, 48, 60, and 72 DAT was 2.58%, 3.90%, 3.29%, 3.03%, 1.89%, 2.24%, and 2.11%, respectively. The largest variation of plant N concentration due to treatments was found between 60 and 72 DAT, whereas the smallest variation occurred at 48 DAT (Figure 1).

Effects of level and timing of N fertilizer application on N uptake

The total N uptake of the treatments where N was applied in 7 splits but in different total amounts (T1, T8, T9, T10 and T11, see Table 1) is shown in Figure 2. The fastest uptake occurred just before active tiller formation and after panicle initiation. Varying the total amount of N applied had mainly an affect on N uptake during panicle formation. After panicle initiation (48 DAT) the uptake rate was faster for higher N levels than for lower N levels. The N uptake at 60 DAT or later differed considerably among the treatments. The total N content from 72 DAT to harvest time did not increase, indicating little N uptake by the crop during that period. Meanwhile, nitrogen was translocated from straw to panicles (Figure 1).

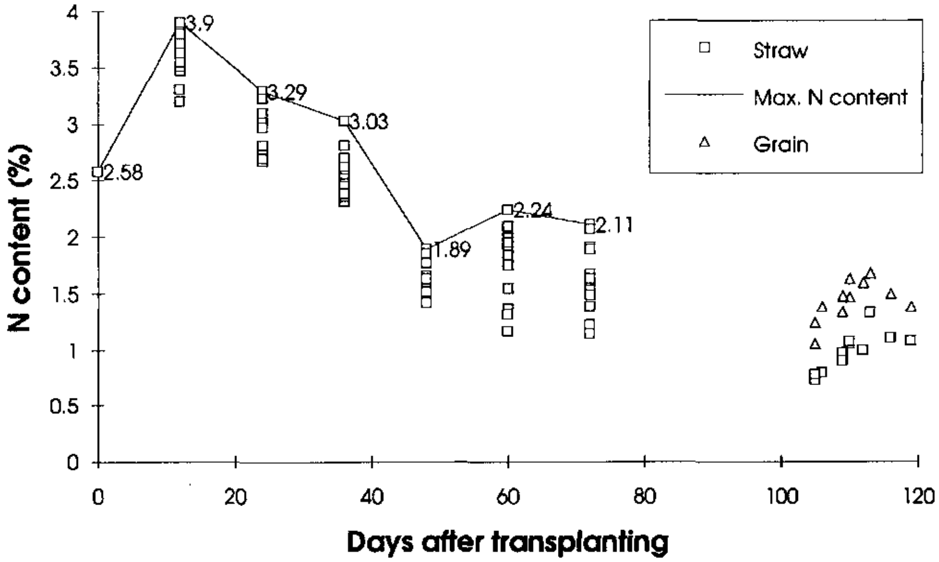

Figure 1. Average N content of rice plant tissue (pooled sample of leaves and stems) at different growth stages for all fertilizer treatments in the field experiment. (Cv. IR64, dry season 1992, Ciwalen, Cipanas). The bold line indicates the maximum N content at any time.

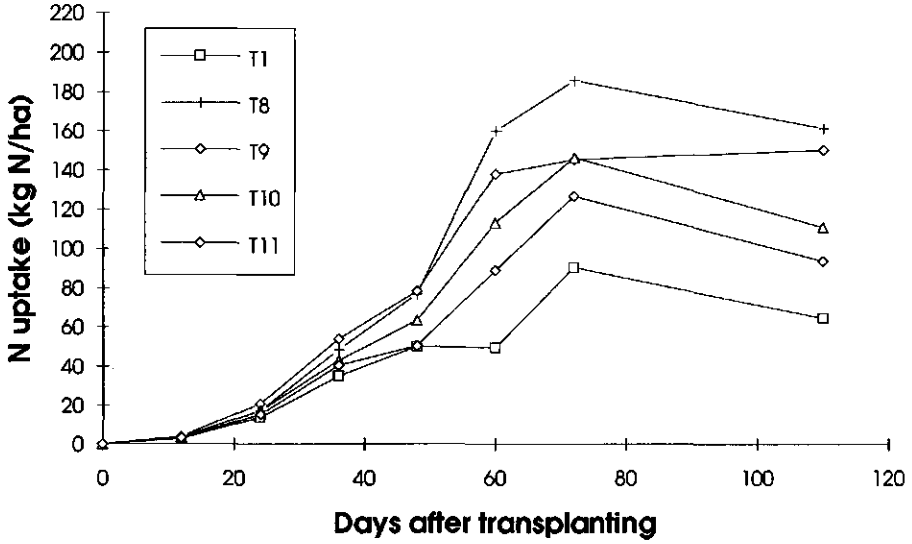

Figure 2. Total N uptake at different growth stages for the field experiment. (Cv. IR64, dry season 1992, Ciwalen). Treatment codes are explained in Table 1.

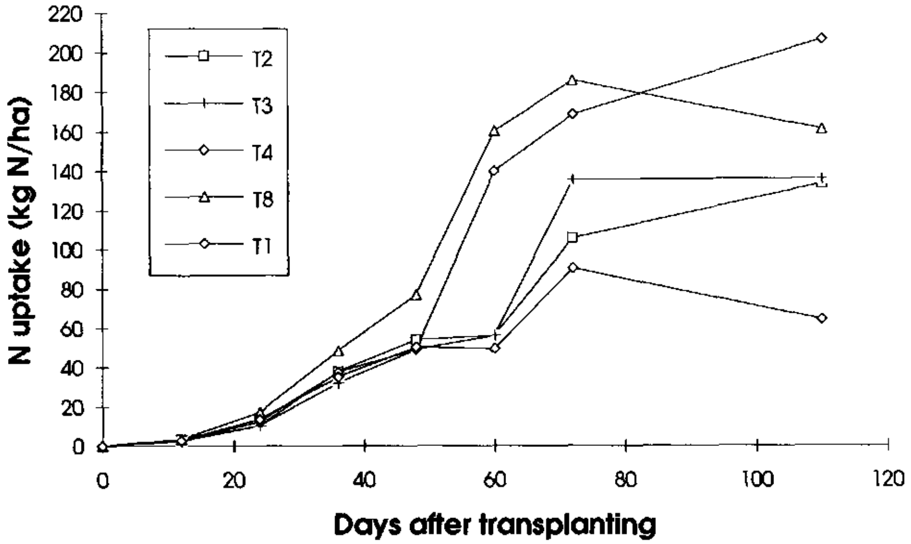

Figure 3. Total N uptake at different growth stages for the field experiment. (Cv. IR64, dry season 1992, Ciwalen). Treatment codes are explained in Table 1.

The effect of N application time on N uptake is shown in Figure 3. Applying 600 kg urea-N/ha at 72 DAT in a single dressing, or in two splits, at 60 and 72 DAT resulted in a similar total N uptake at harvest of about 140 kg N/ha. The largest total N uptake was observed if nitrogen was first applied at 48 DAT (panicle initiation).

The effect of different treatments on total N uptake at harvest is shown in Table 5. T4 and T7 resulted in the largest uptake of N. If N was applied late, i.e. at 60 and 72 DAT (T2, T3), N uptake was low. T2 an T3 had therefore the poorest N fertilizer recovery, whereas T4 and T7 ranked best (Table 5).

The effect of timing and level of urea application on N uptake at harvest was investigated using multiple regression analysis. The following equation was found:

$$\begin{aligned} \text{NUP} = {} & 59.3 + 0.019\ A_0 + 0.384\ A_{12} + 0.069\ A_{24} + 0.037\ A_{36} + 0.468\ A_{48} + \\ & + 0.132\ A_{60} + 0.124\ A_{72} \qquad (r = 0.99) \end{aligned}$$

where:

NUP = total N uptake at harvest for a given treatment in kg N/ha and

A_i = level of N applied at *i* DAT in kg urea/ha.

Table 5. Yields, yield component analysis, total plant N content (kg/ha) at harvest and fertilizer-N recovery for each treatment in the field experiment. (Cv. IR64, dry season 1992, Ciwalen).

Treatment	Total urea (kg/ha)	Panicle nr./hill	% filled grains	1000 grain weight (g)	Grain nr./ panicle	Straw yield (kg/ha)	Grain yield 14% (kg/ha)	N uptake at harvest (kg/ha)	N fert. recovery %
T1	0	13.1	86	27	69.8	3735	3937	64.4	-
T2	600	25.7	70	25.2	69.9	6213	4679	133.8	25.1
T3	600	30.8	68.5	24.2	60.2	5973	5718	136.1	26
T4	600	28.4	70.3	25.8	62.7	7503	6914	206.9	51.6
T5	600	29.1	68.5	25.5	65.9	7492	6658	173.5	39.5
T6	600	25.5	71.2	25.8	70.7	6740	6544	159	34.3
T7	600	21.9	78.1	26.6	68.3	7356	6924	180.8	42.3
T8	600	24.5	66.5	25.9	70.5	8104	6216	161.6	35.2
T9	490	22.3	75.4	26.2	69.6	7153	5942	150.5	38.2
T10	350	19.3	82.4	26.8	66.8	5610	5370	110.9	28.9
T11	210	18.2	81.5	26.6	71.3	5406	4631	93.7	30.4
T12	600	20.5	65.7	25.3	78.1	7789	5493	139.4	27.3

The regression coefficients of the equation indicate the impact of urea application (in kg urea/ha) at a given growth stage (in DAT) on N uptake (kg N/ha). The highest coefficients were found for A_{12} and A_{48}, i.e. 0.384 and 0.468 respectively. Application of fertilizer-N at 12 DAT and at 48 DAT was thus most effective in boosting total N uptake. These dates coincide with active tiller formation stage and panicle formation stage respectively, when the plant is in great need of nitrogen. In contrast, application of urea at transplanting (T0) was least effective with a coefficient of only 0.019. This finding suggests that the first urea application should be delayed up to 12 DAT.

Effect of timing and level of urea application on dry matter production, yield and yield components

The zero-N yield was relatively high (4 t/ha) indicating a good soil N supplying capacity. The first N application could, therefore, be postponed without causing any yield loss. Largest yield was obtained for T7, i.e. if N was applied in 6 equal splits, from 12 DAT onwards, or if the first N application was postponed up to panicle initiation, i.e. T4 (6.9 t/ha). If the first N-application was done at 60 DAT or 72 DAT, yields were slightly lower but were still clearly higher than the zero-N yield. Increasing the urea application level increased grain yield (Figure 4).

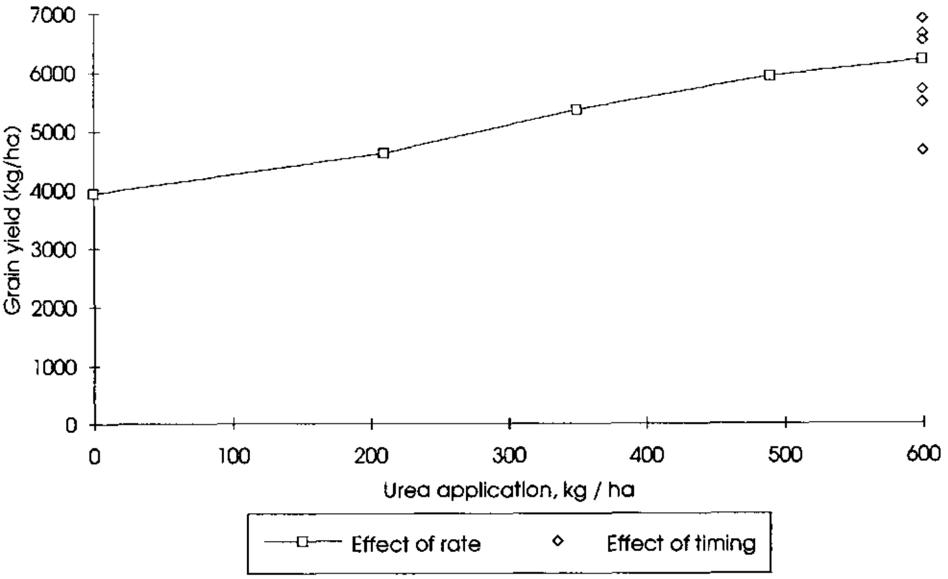

Figure 4. Grain yield as a function of the total amount of applied urea for all treatments. (Cv. IR64, dry season 1992, Ciwalen). Treatment codes are explained in Table 1.

A yield component analysis was conducted to investigate the effect of level and timing of urea application on yield. A higher crop N status increased the number of panicles per hill, but decreased the percentage of filled grains and the 1000 grain weight. Increasing the level of urea application up to 600 kg urea/ha delayed grain ripening and harvest time (Table 2). Harvest area yields were slightly lower than yields computed from the yield components (Table 5).

Late application (60 and 72 DAT) resulted in relatively low 1000 grain weights. Late urea application delayed grain ripening and date of harvest by up to 10 days and increased the number of productive tillers per hill (Table 5).

The impact of urea application in different splits on grain yield was analyzed by multiple regression analysis. This resulted in the following expression:

$$GY = 4286 - 3.55\ A_0 + 8.13\ A_{12} + 3.57\ A_{24} + 2.85\ A_{36} + 9.32\ A_{48} + 4.68\ A_{60} + + 1.22\ A_{72} \qquad (r = 0.96)$$

GY = grain yield in kg/ha and

A_i = level of N applied at *i* DAT in kg urea/ha.

The highest regression coefficients were found for A_{12} and A_{48}, i.e. 8.13 and 9.32, respectively. The results indicate that urea application was most effective at 12 and 48 DAT as was also found by multiple regression analysis for total N uptake.

Physiological efficiency of nitrogen

Yields increased linearly with total plant N uptake. In this experiment yields did not level off, indicating that the maximum yields that can be obtained for this site were not reached, which also follows from Table 5 (20-30% unfilled grains). Physiological efficiency is defined here as the efficiency with which the plant is utilizing absorbed N to produce grain yield. Its value represents the slope of the relation between grain yield and N uptake as shown in Figure 5, which was described as:

$$GY = 2458 + 23.1\ NUP \qquad (r = 0.93)$$

where:

GY = grain yield in kg/ha and
NUP = total N uptake at harvest for a given treatment in kg N/ha

The equation indicates that an increase in N uptake of 1 kg N/ha resulted in an increase in grain yield of 23.1 kg/ha. This value clearly depends on weather conditions and other environmental characteristics.

The effects of level and timing of urea application on tiller formation

Tiller production pattern as a function of urea application level is shown in Figure 6 (only the 7 splits treatments were used here). Tiller number increased up to the panicle initiation stage (48 DAT) and then slowly decreased up to harvest time. However, if 600 kg urea/ha was applied, tiller production was prolonged up to 60 DAT, then decreased. Timing of fertilizer application also affected tiller production pattern (Figure 7, only 600 kg urea/ha treatments are shown). Tiller number increased after N application even if this was at flowering as can be seen from the sharp increase in tiller number for T2 and T3 (Figure 7). The increase in tiller number over each 12 day interval at any stage of crop growth was plotted as a function of average N content of stems and leaves during this 12 day period (Figure 8). From this figure it can be seen that as long as the N content was higher than 1.9%, new tillers were formed. As soon as the N content dropped below this critical value, tiller production stopped, and tiller numbers even decreased.

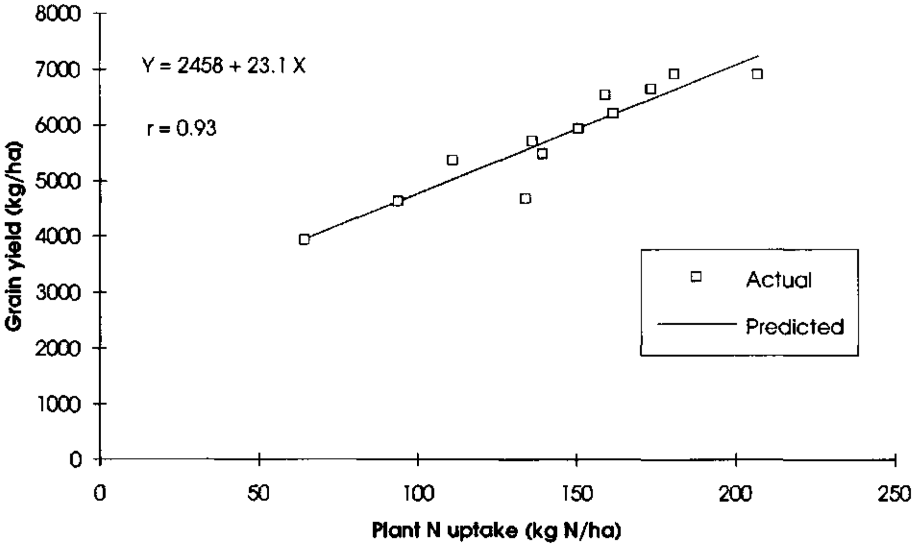

Figure 5. Grain yield as a function of plant N uptake for the field experiment. (Cv. IR64, dry season 1992, Ciwalen). Treatment codes are explained in Table 1.

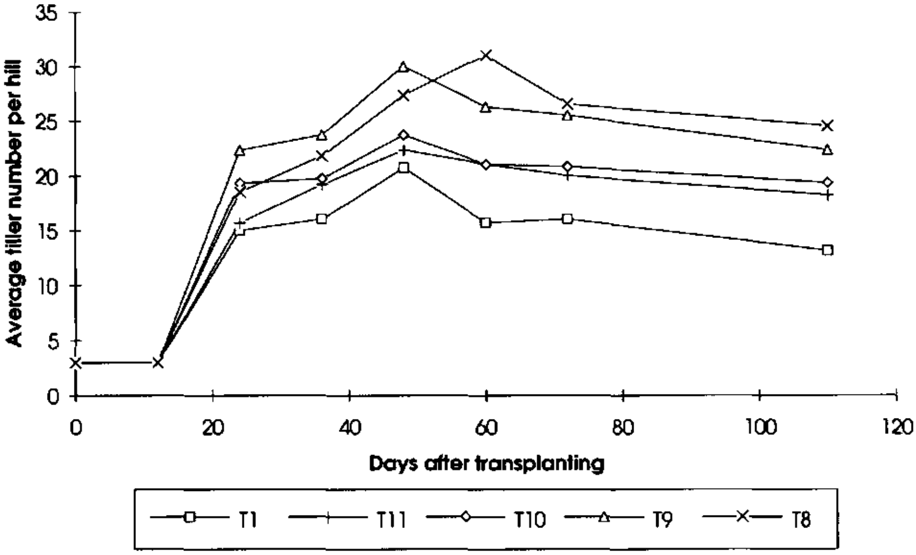

Figure 6. The effect of total amount of applied urea (7 splits treatments) on tiller production in the field experiment. (Cv. IR64, dry season 1992, Ciwalen). Treatment codes are explained in Table 1.

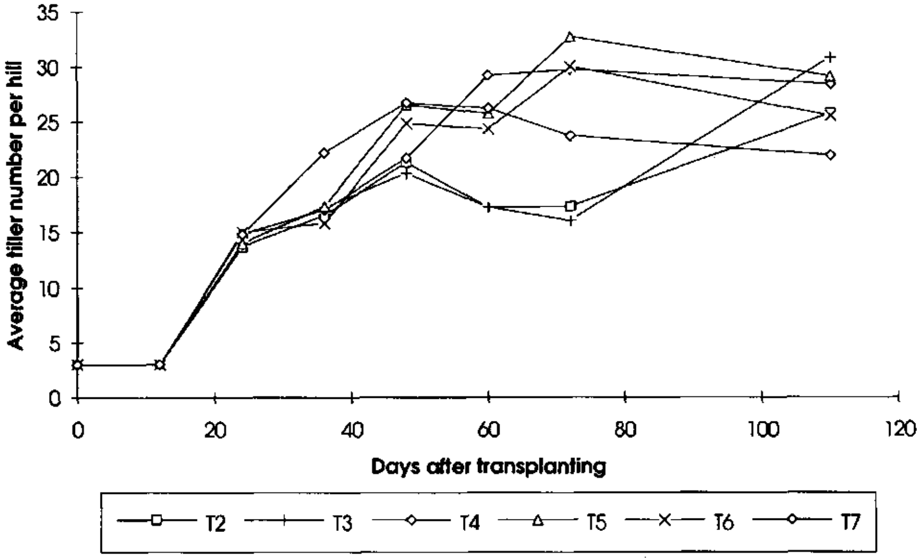

Figure 7. The effect of timing of urea application on tiller production in the field experiment. (Cv. IR64, dry season 1992, Ciwalen). Treatment codes are explained in Table 1.

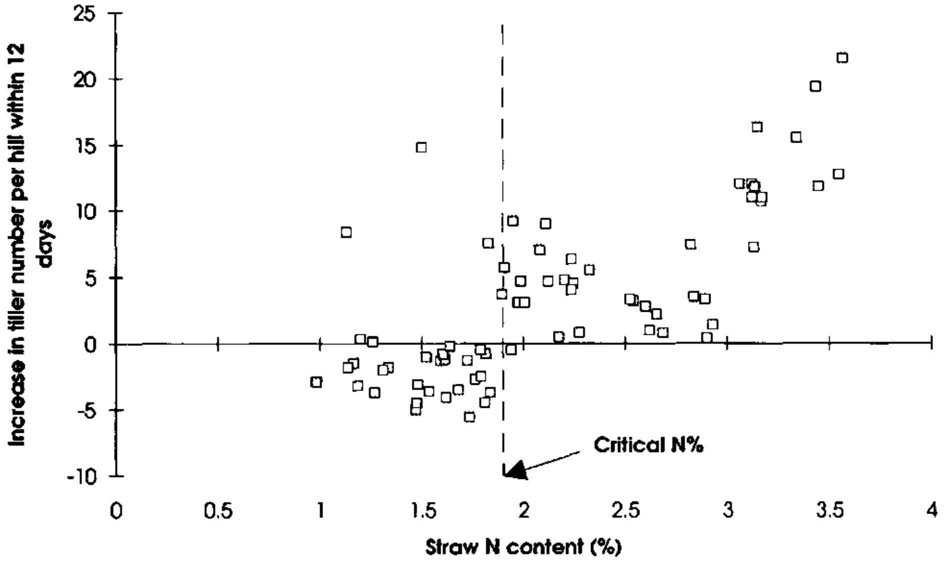

Figure 8. Increase or decrease in the number of tillers per hill in a 12 day period as a function of average plant N content in the field experiment. (Cv. IR64, dry season 1992, Ciwalen).

Conclusions

The nitrogen requirement of irrigated rice varies strongly with growth stage. Growth stage is a good indicator for determining the level and timing of fertilizer N application. Application of N fertilizer at active tillering (12 DAT) and at panicle initiation stage (48 DAT) was most effective in increasing N uptake and grain yield at the Ciwalen site. A critical N content of stems and leaves (1.9%) was derived below which tiller production stopped. Yields increased linearly with total N uptake at harvest, but no plateau level was reached. Postponing the first N-application up to panicle initiation had no serious consequences for final grain yield because of the good N supplying capacity of the soil. Envelope curves of maximum straw N content throughout the crop cycle were derived.

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Nitrogen uptake of irrigated rice and dynamics of soil solution ammonium following N-fertilizer application: a case study for a Haplorthox in West Java, Indonesia

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Abstract

A field experiment was conducted in the non-monsoon season of 1991 in West Java, Indonesia, to study the relation between N uptake of irrigated rice (cv. IR64) and soil ammonium dynamics following N-fertilizer application. Four levels of N (0, 50, 100, 150 kg N/ha) were applied in two equal splits, either at transplanting and 30 days after transplanting (DAT) or at 14 DAT and 30 DAT. The NH_4^+ concentration in the soil solution was monitored up to 33 DAT. Application of N fertilizer at 14 DAT resulted in a greater N uptake, larger yield and a better fertilizer recovery than if the first application was at transplanting. For a total fertilizer dose of 150 kg N/ha this difference in yield was about 1.0 t/ha. The concentration of NH_4^+ in the soil solution increased after each fertilizer application. If N was applied at 14 DAT, the NH_4^+ concentration remained relatively high until the next application at 30 DAT. The concentration of NH_4^+ in the soil solution declined rapidly if N was applied and incorporated at transplanting, possibly due to immobilization of incorporated N by soil microbial biomass.

Introduction

Nitrogen availability is often a limiting factor for growth of irrigated rice. The recovery of fertilizer nitrogen by lowland rice is generally low (30-50%) in the tropics (van Keulen, 1977; Prasad and De Datta, 1979). As a consequence, fertilizer management research often focuses on the fate of nitrogen in the soil-root system. De Willigen and van Noordwijk (1987, 1991) recently introduced a mechanistic model to simulate nutrient uptake by roots. Important variables in this model are the concentration of nutrients in the bulk soil solution, the demand by the crop, and the distribution of active roots in space and over time. The present study was conducted to assess the dynamics of ammonium in the root zone soil solution and to investigate the importance of basal N application, and is a follow-up on the study by Makarim et al. (1991).

Table 1. Root zone chemical and physical soil properties at the experiment site in Bogor, West Java, Indonesia.

Soil property		Value	Method
% Clay		38.9	Pipet
% Silt		48.3	
% Sand		12.9	
pH H_2O		5.85	Glass electrode
pH KCl		5.52	Glass electrode
Total N	(%)	0.17	Kjeldahl
Total C	(%)	1.43	Kurmies
Available P	(ppm)	25	Bray P-2
Available S	(ppm)	16	NH_4OAc pH 4.8
Exch. Ca	(me/100g	2.84	NH_4OAc pH 7.0
Exch. Mg	(me/100g)	1.96	
Exch. K	(me/100g)	0.98	
Exch. Na	(me/100g)	0.22	
Exch. Al	(me/100g)	0.48	1 N KCl
Exch. H	(me/100g)	0.09	1 N KCl
CEC	(me/100g)	18.2	NH_4OAc pH 7.0
Extr. Fe	(ppm)	91	NH_4OAc pH 4.8
Extr. Mn	(ppm)	73	NH_4OAc pH 4.8
Available Cu	(ppm)	5	0.1 N HCl
Available Zn	(ppm)	16	0.1 N HCl

Table 2. Overview of nitrogen fertilizer treatments used in the experiment. Bogor, dry season, 1991.

Code	0 DAT (kg/ha)	14 DAT (kg/ha)	30 DAT (kg/ha)	Total (kg/ha)
T1	0	0	0	0
T2	25	0	25	50
T3	0	25	25	50
T4	50	0	50	100
T5	0	50	50	100
T6	75	0	75	150
T7	0	75	75	150

Materials and Methods

The field experiment was conducted in Bogor, West Java, Indonesia in the dry season of 1991. Soil characteristics of the root zone, determined just before the start of the field experiment, are shown in Table 1. The soil was classified according to Soil Taxonomy as a Haplorthox (Soil Survey Staff, 1975). Rice cultivar IR64 was transplanted in puddled soil on 6 June 1991 (21 days old seedlings, 3 seedlings per hill, 20 cm x 20 cm plant spacing). P and K fertilizer were applied basally at 50 kg/ha. Four levels of N (0, 50, 100 and 150 kg N/ha) were applied in two equal splits, either at transplanting and 30 DAT or at 14 DAT and 30 DAT (Table 2). The treatments were arranged in a complete randomized block design with three replicates, using 6m x 5m experimental plots, which remained flooded throughout the experiment. Soil solution was collected periodically upto 33 DAT by suction using 12 cm long microporous synthetic tubes (inner diameter: 1 mm, pore size: 0.1 µm). The soil solution samples (10 ml) were obtained by suction using a syringe. Samplers were fixed horizontally in the puddled topsoil of each plot by stainless steel wire frames at a depth of 7.5 cm below the soil surface. The NH_4^+-N concentration in the soil solution was determined colorimetrically. At harvest, grain yield (6 m^2 sampling area) and total N uptake (6 hills excluding roots) were determined. Plant N content was determined by the Kjeldahl method.

Results and discussion

Panicle initiation was observed around 16 July 1991 and heading (80% of all hills) on 7 August 1991 for all treatments. All plots were harvested on 7 September 1991.

Ammonium in soil solution

The pattern of NH_4^+-N in the soil solution was strongly dependent on the time of urea application as indicated in Figures 1 and 2. The NH concentration declined rapidly if N was applied at transplanting, reaching a minimum value at 21 DAT. The concentration increased again after the second application. Broadcasting the first N dose at 14 DAT resulted in a relatively high concentration of NH_4^+-N in the soil solution up to the second application at 30 DAT. The rate of N concentration decline was, therefore, dependent on the moment of fertilizer application and possibly related to the incorporation of N at transplanting. This may have resulted in increased immobilization of N by the soil microbial biomass, because the availability of carbon per unit available nitrogen is higher in case of incorporation. The lower increase of N concentration at 30 DAT in Figure 1 as compared to Figure 2 is ascribed to the higher uptake rate by the low N crop in Figure 1.

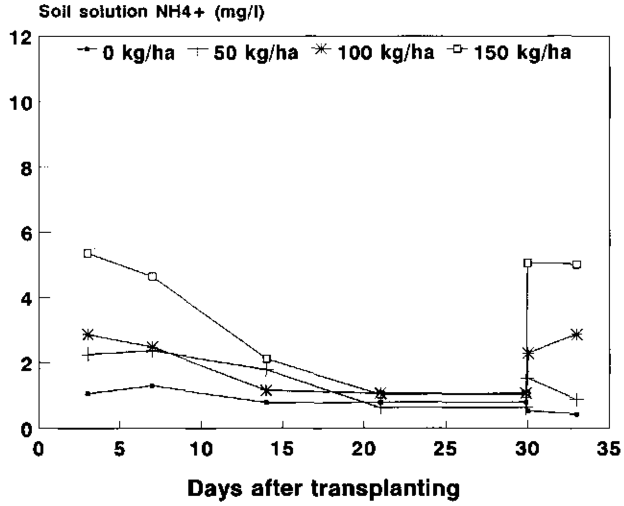

Figure 1. Ammonium concentration in soil solution after application of four nitrogen levels at 0 and 30 days after transplanting (DAT). Cv. IR64, Bogor, dry season 1991. Treatment codes are explained in Table 2.

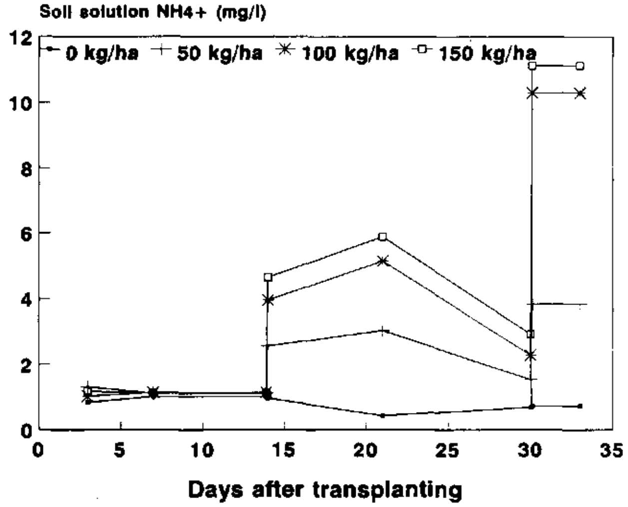

Figure 2. Ammonium concentration in soil solution after application of four nitrogen levels at 14 and 30 days after transplanting (DAT). Cv. IR64, Bogor, dry season 1991. Treatment codes are explained in Table 2.

Table 3. Effect of level and timing of urea application on N uptake, fertilizer recovery and grain yield. Cv. IR64, Bogor, dry season, 1991. Treatment codes are explained in Table 2.

Code	Total N-uptake (kg/ha)	N-fertilizer recovery (%)	Yield 14% m.c (t/ha)
T1	68	-	3.65
T2	90	43	4.11
T3	93	50	4.17
T4	105	36	4.91
T5	124	56	5.70
T6	116	32	5.03
T7	156	58	6.03

N fertilizer efficiency

Postponing the first N-application up to 14 DAT improved fertilizer recovery (Table 3), presumably by giving the rice plants time to develop roots and then offering a high NH_4^+ concentration in the soil solution during the active tillering stage (i.e. 14-30 DAT, Figure 2) when demand is high. This also increased yield (Table 3). The effect of postponing the first N application on grain yield was more pronounced at higher total levels of N. At the highest level (i.e. 150 kg N/ha) postponing the first N application to 14 DAT resulted in about 1 ton/ha extra yield.

Conclusions

Fertilizer recovery and grain yield at the experimental site improved considerably if the first N-application was postponed to 14 DAT. Application of N fertilizer at 14 DAT resulted in a higher N uptake, yield and fertilizer recovery than if the first application was done at transplanting. At 150 kg N/ha the yield difference was about 1.0 t/ha. The concentration of NH_4^+ in the soil solution increased after each fertilizer application. If N was broadcast at 14 DAT and not incorporated, the NH_4^+ concentration remained high until the next application at 30 DAT. If N was applied at transplanting and incorporated into the soil, a rapid decline in the concentration of NH_4^+ in the soil solution was observed, possibly due to immobilization by soil microbial biomass.

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Nitrogen uptake and yield formation of rice cvar IR64 under different urea application strategies on an alluvial ultisol in West Java

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Abstract

Nitrogen (N) fertilizer applied after panicle initiation (PI) stage did not result in increased grain yield and yield components of rice cvar IR64 during two seasons at Sukamandi, West Java. The highest grain yields in the wet season and the dry season were 4.97 t/ha and 4.67 t/ha, respectively. Best yields were attained when N was applied in 3 to 5 splits, with the first dressing no later than 28 days after transplanting (DAT). The maximum wet season grain yield was reached with 135 kg N/ha given at planting time; the best result in the dry season, where all treatments received 200 kg N/ha, was obtained with a three split application, at 0, 14 and 28 DAT.

Post-PI uptake of available N was very low in both experiments. This is ascribed to either a low crop demand for N arising from limited tillering at earlier stages, or to the inability of the root system at later stages to acquire available nitrogen. The underlying factor(s) could not be identified from the current experiments.

In the Sukamandi area, dry season yields are lower than wet season yields. Observations of panicle number, spikelet number per panicle (primary panicles), grain filling, and the percentage of filled spikelets showed that yield limitations are directly related to the number of productive panicles formed, and not to spikelet fertility, fecundation, or grain filling percentage.

Introduction

Improving the efficiency of mineral fertilizers to meet the growing demands of agricultural produce, particularly rice, is an important goal of agricultural research in many developing countries. This need was recently reinforced in Indonesia, since fertilizer subsidies were reduced. Efforts should focus on the question how economically feasible input levels can be maintained, while increasing absolute production levels at the same time. This requires an understanding of the basic processes underlying uptake and utilization of nutrients by the crop.

Nitrogen is an important input in rice production. The response of the rice plants to nitrogen application is affected by varietal characteristics, soil conditions, weather and management practices, particularly timing and method of N application (De Datta and Magnaye, 1969). Tanaka et al. (1959) reported that split application of N, one dose at transplanting and the other at panicle initiation, was the best procedure to obtain high grain yields, particularly in the case of medium and long duration varieties. De Datta et al. (1974) indicated that short duration rice cvars respond best to N applied just before panicle initiation. According to Sharma et al. (1989), yield from plants fertilized soon after the first weeding was significantly higher than that from plots fertilized at transplanting. Optimal methods of N application are also closely related to the physiology of yield-determining characteristics.

N is easily lost from soil and floodwater by volatilization, denitrification, and leaching. The recovery of fertilizer nitrogen by rice under lowland conditions is often low, but can be quite variable. (Van Keulen, 1977; other contributions in this issue). Losses of nitrogen from urea are known to range from 60 to 80% for rice, while figures of 40 to 60% generally apply to upland crops (Stangel, 1977).

Irrespective of the wealth of literature available on N fertilizer recovery, N losses, and rice responses to N application, it is often not clear whether, in a particular location, low recoveries are the result of high loss rates, or should be ascribed to poor uptake capacity of the root system.

The study covered by this paper aims at clarifying this issue for the Sukamandi region, an important rice production area in West Java, Indonesia.

Materials and methods

The effects of nitrogen application time and dose on yield formation and N uptake by rice cvar IR64 were studied in two field experiments. Both experiments were conducted at the SURIF experiment station at Sukamandi, West Java, Indonesia on an alluvial hydromorphic ultisol. One experiment was carried out during the wet season of 1991 - 1992 (WS91-92), the other during the 1992 dry season (DS92).

Both experiments were laid out in a randomized block design with three replications. Plot size was 5 m x 6 m in WS91-92, and 4 m x 5 m in DS92. 21 d old seedlings were transplanted at 20 cm x 20 cm spacing in both cases, one seedling per hill. Triple-superphosphate and KCl fertilizers were incorporated at transplanting at rates equivalent to 60 kg P_2O_5 and 30 kg K_2O, respectively.

Nitrogen application was always in the form of 1 g urea briquettes placed manually in batches at the centre of each set of four hills, at approximately 10 cm depth, the batch size depending on the N dose. The soil was puddled and continuously flooded from land preparation prior to transplanting to maturity.

Table 1a. Urea dose and application scheme for the different treatments in the 1991 - 1992 wet season experiment. Sukamandi, West Java, Indonesia.

Treatment	Total dosage urea-N (kg/ha)	Time of application			
		Planting	Active Tillering	Panicle Initiation	10% Flowering
		N applied (kg/ha)			
T1	0	0	0	0	0
T2	45	0	0	45	0
T3	45	45	0	0	0
T4	90	45	0	45	0
T5	90	90	0	0	0
T6	90	0	0	90	0
T7	135	45	0	90	0
T8	135	90	0	45	0
T9	135	0	0	135	0
T10	135	135	0	0	0
T11	180	90	0	90	0
T12	180	45	45	45	45
T13	135	45	45	45	0
T14	135	0	45	45	45
T15	135	45	0	45	45
T16	135	45	45	0	45

WS91-92 experiment

Details of the sixteen treatments in the WS91-92 experiment, combining various N application doses and timings, are listed in Table 1a. The total dose varied from 0 to 180 kg N/ha, and treatments included fertilizer dressings at transplanting (November 28), active tillering (21 days after transplanting, DAT), panicle initiation (42 DAT), and at the 10% flowering stage (65 DAT). The crop was harvested on March 4 1992 (96 DAT).

Samples for growth analysis were collected every 2 weeks during the first 8 weeks after transplanting. Samples for determination of plant N content were collected at panicle initiation stage, at 10% flowering stage and at maturity. The samples were split into leaves, stems (including leaf sheaths), roots and panicles, and their dry weights and N contents (by Kjeldahl method) were determined.

Observations on mean spikelet weight were made every 3 d after flowering, up to maturity. Final yield was determined from a 12 m^2 harvest area.

Table 1b. Urea dose and application scheme for the different treatments in the 1992 dry season experiment. Sukamandi, West Java, Indonesia.

Treatment	Total dosage urea-N (kg/ha)	Time of application (DAT)						
		0	14	28	42	56	70	84
		N applied (kg/ha)						
T1	0	0	0	0	0	0	0	0
T2	200	0	0	100	100	0	0	0
T3	200	0	0	0	0	0	100	100
T4	200	66.6	66.6	66.6	0	0	0	0
T5	200	0	66.6	66.6	66.6	0	0	0
T6	200	0	0	0	0	66.6	66.6	66.6
T7	200	0	50	50	50	50	0	0
T8	200	0	0	0	50	50	50	50
T9	200	40	40	40	40	40	0	0
T10	200	0	0	40	40	40	40	40
T11	200	0	33.3	33.3	33.3	33.3	33.3	33.3

DS92 experiment

The eleven treatments imposed in the DS92 experiment are specified in Table 1b. An amount of 200 kg N/ha was applied in all treatments except the control treatment, but the number of splits and timing varied widely among treatments. Seedlings were transplanted on May 7, 1992. Plant samples, three hills per plot, were collected for N content determination at panicle initiation (42 DAT) and at maturity (102 DAT). Samples for growth analysis were collected at 14, 28, 42, 56, 70, and 94 DAT. First heading occurred at 56 DAT. At harvest, yield components were determined by collecting the primary panicle from 10 hills. Final grain yield was measured from a 12 m^2 harvest area, on 9 August 1992 (94 DAT).

Results and discussion

Biomass and yield, WS91-92 experiment

The observed biomass values of the various plant organs are listed in Table 2 for the WS91-92 experiment. Time courses of total crop biomass are given in Figure 1. Final biomass of plant organs at harvest is given in Figure 2.

Table 2. Effect of N application dose and scheme on biomass of plant organs on various sampling dates. Rice cvar IR64, 1991-1992 wet season, Sukamandi, West Java. Treatment codes are explained in Table 1a.

	T1	T2	T3	T4	T5	T6	T7	T8
DAT	Biomass (kg/ha) of green leaves							
14	64.58	99.03	79.31	71.94	95.97	85.97	80.14	108.06
28	454.44	613.75	605.28	749.03	770.14	723.47	706.81	763.89
42	894.38	956.46	1023.54	1015.83	1353.75	919.58	1076.46	1364.79
56	1255.42	1309.17	1728.75	1207.92	1750.42	1337.92	1142.50	1193.33
70	1322.22	1539.58	1568.47	1471.67	1916.67	1389.72	1402.08	1623.75
84	816.39	1032.92	961.11	1404.58	1109.58	1188.75	1251.53	1488.75
96	931.25	838.54	1020.21	936.04	973.75	927.29	950.63	1095.42
	Biomass (kg/ha) of stems (incl. sheaths)							
14	87.08	88.19	84.86	76.94	116.11	141.39	107.50	124.72
28	566.94	770.69	701.67	835.00	831.25	818.89	823.89	912.50
42	2273.75	1903.75	1759.58	2202.08	3097.50	1817.71	2582.50	2902.92
56	2689.31	2429.31	2867.36	2553.19	3222.50	2133.75	2637.78	3099.58
70	2927.08	3262.50	3171.67	3028.33	3292.08	2555.00	2972.08	3468.33
84	3033.89	3537.36	3476.67	3933.47	3474.44	2942.08	3500.28	3945.56
96	2148.54	2408.75	3226.46	3410.63	2516.46	2364.79	2412.92	3068.33
	Biomass (kg/ha) of roots							
14	87.08	88.19	84.86	76.94	116.11	141.39	107.50	124.72
28	677.50	872.36	821.67	1243.47	1055.42	1072.78	1045.14	1200.42
42	1159.58	1193.33	1328.54	1688.96	1650.21	1642.50	1553.96	2358.75
56	1681.67	2112.92	1920.69	1965.00	1676.67	1707.08	1706.81	2647.78
70	2523.33	2946.25	2752.92	2556.67	3065.83	2597.50	2873.33	3077.08
84	2460.83	2881.53	2410.42	2584.58	2847.36	2214.58	2350.97	3063.75
96	2285.21	2254.17	2238.33	2445.83	2006.67	2014.17	1462.50	2132.92
	Biomass (kg/ha) of panicles							
84	1446.67	2769.03	2117.92	2780.97	2107.50	2211.11	2652.50	3037.08
96	2702.67	4357.08	4495.42	4577.92	4658.75	4550.83	4393.33	4236.67

(continued next page)

Table 2 (continued)

DAT	T9	T10	T11	T12	T13	T14	T15	T16
	Biomass (kg/ha) of green leaves							
14	78.19	79.86	72.64	72.22	90.97	79.03	75.00	79.17
28	684.17	728.33	530.56	558.19	582.92	701.53	732.08	660.28
42	943.54	1257.50	1113.33	1275.00	1363.96	1236.25	1207.71	1431.67
56	1389.58	1585.83	1536.67	1649.58	1320.42	1429.17	1398.75	1598.33
70	1538.75	1990.83	1594.31	1671.11	1742.92	1562.64	1545.97	1912.50
84	1280.97	1403.61	1346.25	1586.53	1598.75	1355.42	1118.61	1310.14
96	937.92	1208.96	1001.46	983.54	922.08	1147.08	983.33	1159.17
	Biomass (kg/ha) of stems (incl. sheaths)							
14	95.69	114.31	83.06	80.56	100.28	89.17	107.22	77.92
28	672.08	848.61	680.14	736.81	630.00	597.64	922.08	682.92
42	2474.38	2190.63	2455.42	2774.79	2749.58	1987.92	2663.54	2192.71
56	2729.44	3097.64	2613.89	2714.03	2851.25	2399.86	3075.00	2991.67
70	2881.25	3375.42	3447.08	3312.92	3469.17	3594.58	3283.33	3408.33
84	3202.92	4117.64	4058.75	3773.89	3913.75	4012.64	3713.75	3763.47
96	2776.67	2839.58	2518.13	3220.83	2892.29	2883.75	2275.83	3214.17
	Biomass (kg/ha) of roots							
14	95.69	114.31	83.06	80.56	100.28	89.17	107.22	77.92
28	1588.75	883.75	956.67	1020.97	922.78	1140.69	1003.47	1054.44
42	1798.75	1535.63	1250.63	1708.13	1677.08	1704.58	1695.00	1939.17
56	2204.58	2825.97	1816.39	1812.08	1811.39	2420.42	1967.08	2313.19
70	2672.50	3103.75	2232.92	3062.08	2680.83	2552.92	2098.75	2510.42
84	2245.83	2361.53	2604.03	2619.44	3080.42	2837.08	2407.08	2868.19
96	1996.25	1952.92	2290.42	2301.67	2391.88	2070.00	2110.83	2481.25
	Biomass (kg/ha) of panicles							
84	2338.89	2446.67	2517.78	2710.42	2038.61	2227.22	2225.97	2316.53
96	4820.42	4971.25	4699.38	4878.75	4700.42	4682.92	4613.96	4155.83

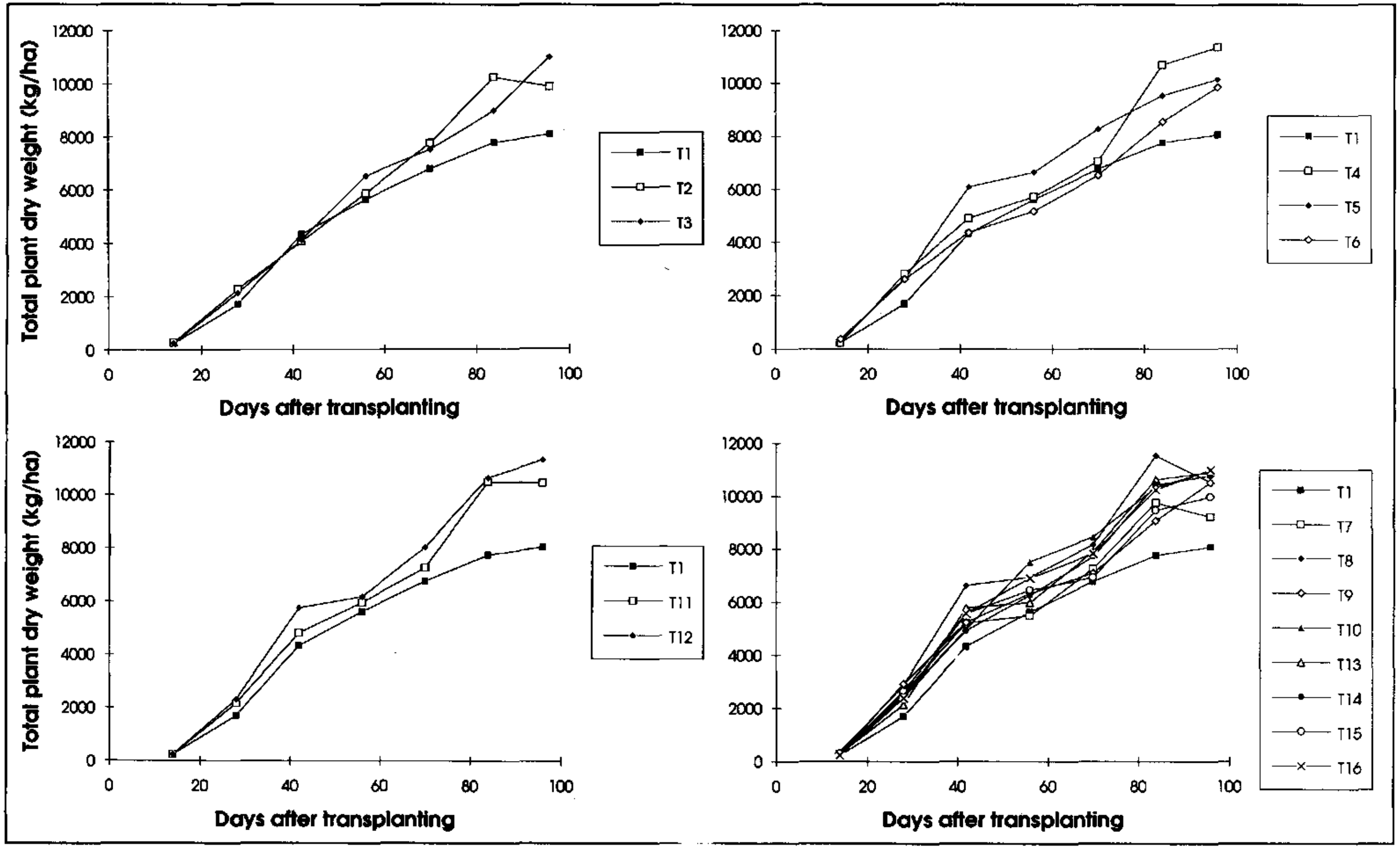

Figure 1a-1d. Effect of N application dose and scheme on total crop biomass (incl. roots). Rice cvar IR64, 1991-1992 wet season, Sukamandi, West Java.

Rate and time of urea application had a marked effect on dry weights of stems and roots, whereas leaf and panicle weights were not much affected. Differences between treatments became significant starting from 42 DAT. Leaf and root growth ceased after 70 DAT, while the stem dry weight continued to increase untill 84 DAT. This suggests that the rate of assimilate supply exceeded the absorption capacity of the spikelets. Maintaining a high crop growth rate up to or beyond flowering stage as a result of later N application is therefore not to be recommended in the Sukamandi area, in view of nitrogen use efficiency.

Application of 135 kg N ha^{-1} at transplanting resulted in the highest grain weight (4971 kg/ ha). This was, however, not significantly different from the grain weights obtained in the plots that received 90 kg N ha^{-1} (4658 kg/ha), or 180 kg N ha (4878 kg/ha).

Although urea application up to 180 kg N /ha resulted in higher biomass of stems and leaves, this was not associated with higher grain yields. The maximum and minimum grain : straw ratio's attained were 1.42 and 0.88. Application of more than 90 kg N ha^{-1} after panicle initiation increased non economic yield. The yield components of the WS91-92 experiment are given in Table 3.

N uptake, WS91-92 experiment

The different treatments caused a high variation in N contents of plant organs at any stage of plant growth (Table 4). The maximum leaf N concentration was 2.49% at panicle initiation stage, obtained in the treatment that received 135 kg N ha^{-1} at transplanting. This N treatment also showed the highest accumulation of N in the grains. Statisticaly, there were no differences - among all treatments that received fertilizer N - in the N fraction of plant organs. Total crop N uptake at various stages is plotted in Figure 3. Total amounts of N accumulated in the plant organs at harvest are given in Figure 4.

Biomass and yield, DS92 experiment

Growth curves are given in Figure 5 for all treatments. Weights of plant organs are listed in Table 5. Figure 6 shows the final biomass of plant organs at harvest. The total crop biomass increased as a result of N application in treatments T4, T7, T10, and T11. All curves show a growth reduction before flowering, followed by increased growth after flowering. This suggests that a negative feedback involving assimilation rate and assimilate storage reduced preflowering growth due to a limited sink size for carbohydrates.

N application significantly affected grain yield. Yield increased by 37 to 93% due to the application of N. The highest yields were attained when N was applied early (T4, T5, T7, T10). In these treatments, rice yields were 80-90% higher than in the control. The highest grain yield of 4.67 t/ha was obtained from the plots that received N at 0, 14, and 28 DAT (T4). Grain yields were not significantly different among treatments where N was applied before or at 28 DAT, except for the T2 treatment, where the doses may have been too high. The grain yields were generally lower when the first N application was later than 28 DAT.

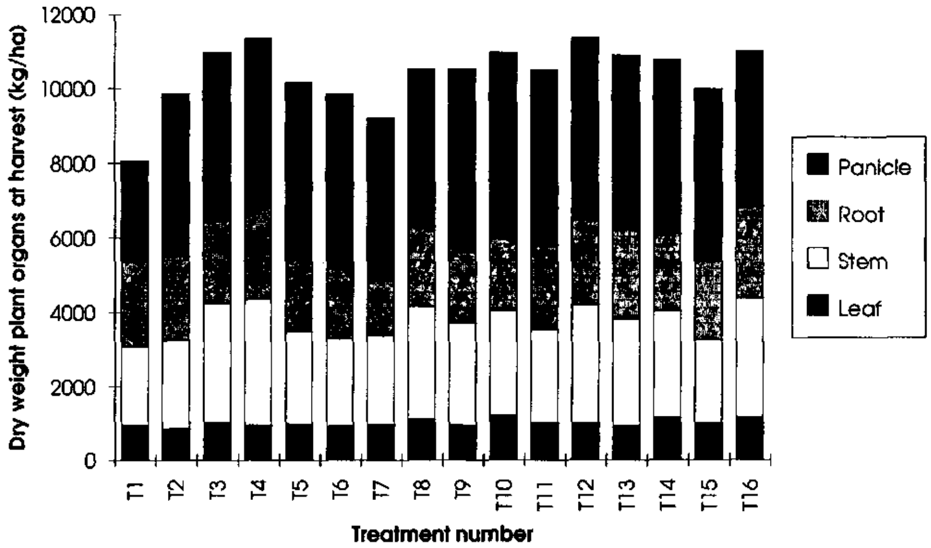

Figure 2. Effect of N application dose and scheme on distribution of biomass at harvest. Rice cvar IR64, 1991-1992 wet season, Sukamandi, West Java. Treatment codes are explained in Table 1a.

Table 3. Effect of N application dose and scheme on yield components. Rice cvar IR64, 1991 - 1992 wet season, Sukamandi, West Java. Values marked with common letters are not significantly different according to Duncan's Multiple Range Test.

Treatment	yield kg/ha		number of prod. tillers /hill		number of filled grains on primary panicle		number of unfilled grains on primary panicle		1000 grains weight (g)	
T1	3299.09	c	12.4	e	75	a	12	bc	27.1	bc
T2	3517.17	bc	14.8	cd	75	a	18	a	27.2	b
T3	3691.38	bc	14.1	de	75	a	14	abc	27.3	ab
T4	3703.71	bc	15.7	cd	90	a	15	abc	27.3	ab
T5	3937.50	bc	17.2	bcd	78	a	11	c	27.4	ab
T6	5085.03	ab	16.1	bcd	73	a	19	a	26.8	bc
T7	4363.13	bc	16.0	bcd	82	a	15	abc	27.2	b
T8	4484.12	abc	16.8	bcd	76	a	16	abc	27.3	ab
T9	4545.41	abc	16.6	bcd	85	a	17	ab	26.3	c
T10	6139.36	a	18.0	b	77	a	14	abc	27.4	ab
T11	4404.19	bc	17.4	bcd	74	a	18	a	27.2	b
T12	4221.40	bc	16.7	bcd	84	a	17	ab	27.4	ab
T13	4831.19	abc	21.6	a	73	a	17	ab	27.1	bc
T14	4093.97	bc	15.9	bcd	76	a	16	ab	27.3	ab
T15	4989.40	abc	15.8	bcd	74	a	16	ab	26.9	bc
T16	4740.00	abc	18.4	b	76	a	13	abc	28.1	a

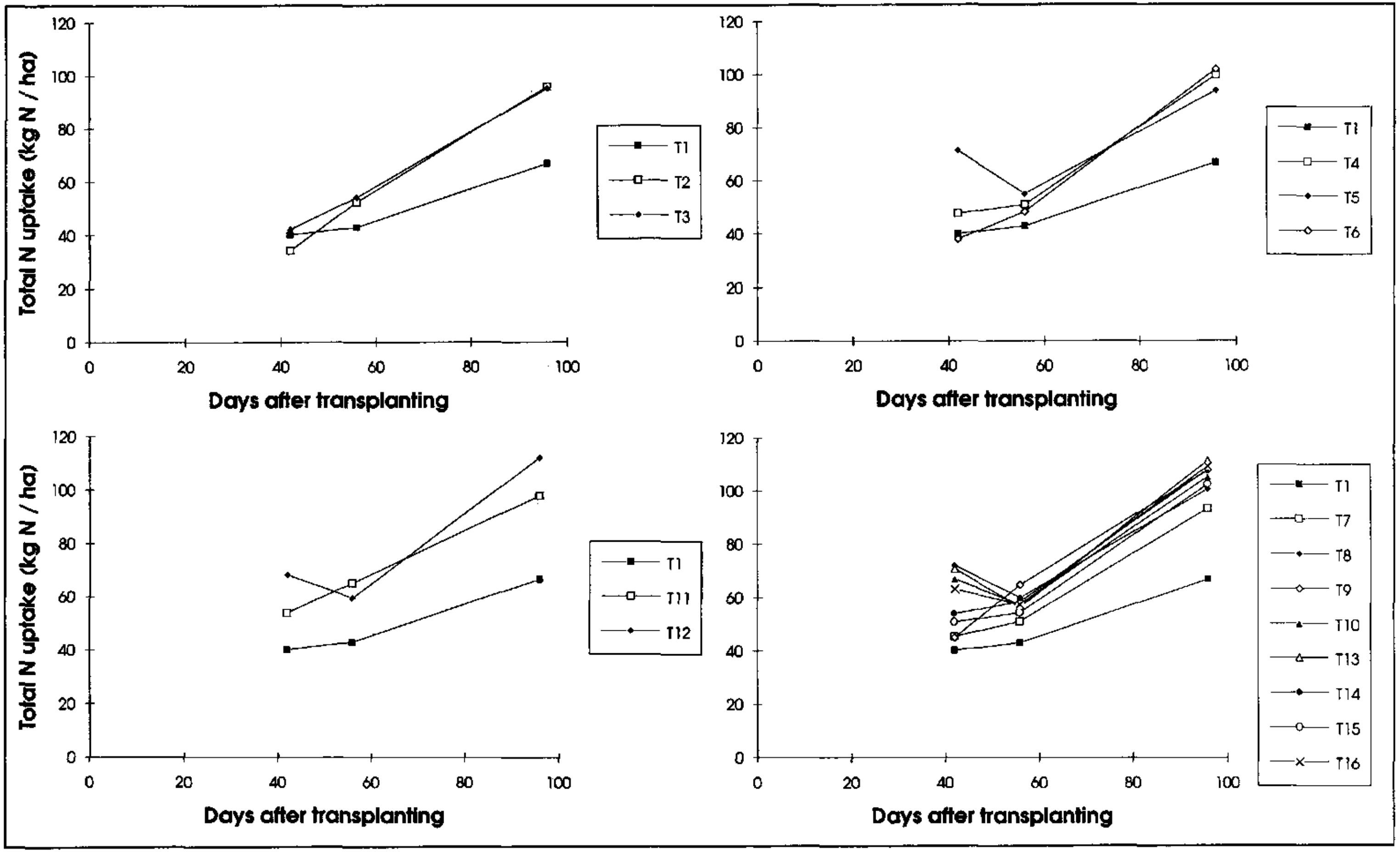

Figure 3a-3d. Effect of N application dose and scheme on total N uptake by the crop. Rice cvar IR64, 1991-1992 wet season, Sukamandi, West Java. Treatment codes are explained in Table 1a.

Table 4. Effect of N application dose and scheme on N contents of plant organs on various sampling dates. Rice cvar IR64, 1991 - 1992 wet season, Sukamandi, West Java. Treatment codes are explained in Table 1a.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16
DAT	N content (%) of green leaves															
42	1.93	1.80	2.23	2.00	2.28	1.92	1.89	2.15	1.94	2.49	2.26	2.26	2.35	2.35	1.82	2.31
56	1.61	1.89	1.68	2.03	1.70	1.87	2.00	2.11	2.30	1.90	2.23	1.92	2.07	2.11	2.00	1.83
96	1.01	1.38	1.08	1.07	0.89	1.15	1.11	1.09	1.08	0.97	1.16	1.17	1.00	1.14	1.15	1.36
	N content (%) of stems (incl. sheaths)															
42	0.83	0.66	0.85	1.02	1.16	0.78	0.81	1.17	0.87	1.38	1.01	1.21	1.23	1.00	0.85	1.07
56	0.61	0.77	0.61	0.76	0.63	0.83	0.83	0.77	0.92	0.62	0.93	0.77	0.78	0.85	0.67	0.65
96	0.64	0.66	0.69	0.69	0.75	0.77	0.67	0.81	0.71	0.61	0.76	0.83	0.74	0.83	0.77	0.82
	N content (%) of roots															
42	0.36	0.39	0.35	0.30	0.30	0.39	0.28	0.38	0.29	0.36	0.33	0.37	0.31	0.30	0.38	0.35
56	0.39	0.43	0.41	0.37	0.31	0.34	0.38	0.42	0.36	0.29	0.38	0.40	0.39	0.34	0.31	0.38
96	0.44	0.46	0.38	0.39	0.48	0.44	0.48	0.50	0.52	0.42	0.53	0.33	0.45	0.42	0.43	0.40
	N content (%) of grains															
96	1.26	1.34	1.20	1.25	1.23	1.42	1.36	1.26	1.40	1.38	1.18	1.37	1.50	1.34	1.41	1.38

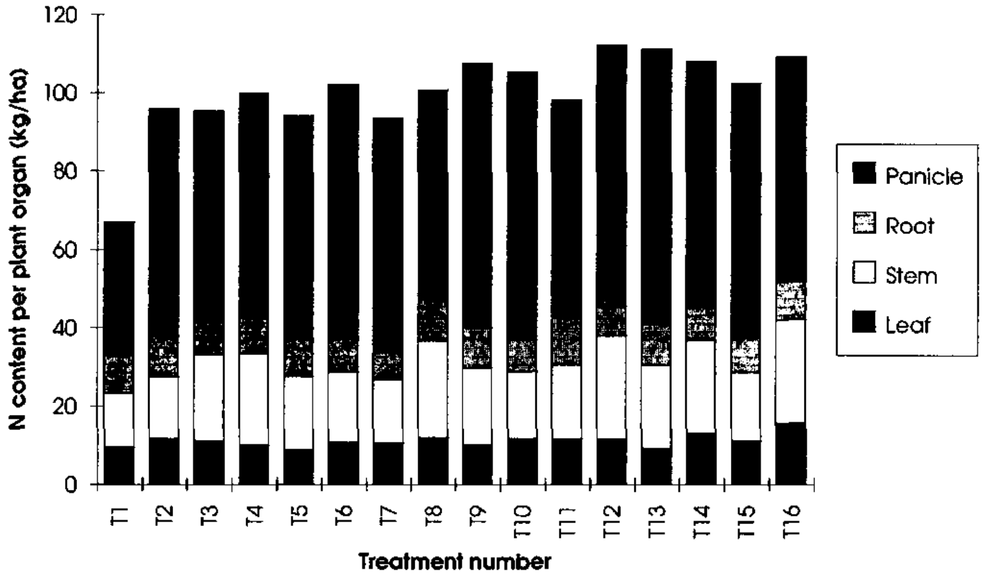

Figure 4. Effect of N application dose and scheme on distribution of crop N at harvest. Rice cvar IR64, 1991-1992 wet season, Sukamandi, West Java. Treatment codes are explained in Table 1a.

Table 5. Effect of N application dose and scheme on biomass of plant organs on various sampling dates. Rice cvar IR64, 1992 dry season, Sukamandi, West Java. Treatment codes are explained in Table 1b.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
	Biomass (kg/ha) of green leaves										
DAT											
14	93.50	70.67	70.67	70.67	70.67	70.67	70.50	70.00	74.50	65.83	79.33
28	633.50	430.50	477.50	470.00	325.67	294.00	354.33	421.00	498.00	474.50	369.17
42	868.00	923.50	532.83	681.50	545.83	462.33	805.67	584.17	605.50	724.50	771.00
56	923.33	959.50	799.00	971.50	834.50	802.00	967.50	825.00	880.50	975.50	836.00
70	794.00	752.00	716.00	870.50	707.50	652.50	855.50	681.00	846.00	777.00	796.50
94	525.50	647.00	512.00	658.00	643.00	574.00	617.50	453.50	567.00	660.50	642.00
	Biomass (kg/ha) of stems (incl. sheaths)										
14	50.50	67.83	67.83	72.50	67.83	67.83	72.50	62.83	58.33	51.67	74.33
28	514.00	452.50	304.33	527.50	327.00	480.00	472.50	441.00	458.00	446.00	524.00
42	928.00	989.00	590.33	1084.00	708.83	782.00	793.83	719.50	790.00	988.00	815.67
56	1284.50	1072.67	891.00	1459.50	1015.33	818.83	901.67	1018.83	1242.00	1462.33	1409.00
70	1499.50	1642.00	2131.00	2183.50	1192.00	1427.00	1399.00	1553.00	1720.00	2108.50	1639.00
94	2327.50	2420.00	2394.50	2488.50	2182.00	2102.00	2119.50	1918.67	2329.33	2174.00	2298.83
	Biomass (kg/ha) of roots										
14	84.00	98.50	53.50	56.50	48.33	58.50	61.50	53.50	61.50	65.83	95.50
28	462.33	483.00	482.00	482.50	406.00	477.00	486.50	467.50	502.50	450.50	479.50
42	903.50	661.00	712.00	547.50	692.50	792.00	754.00	839.00	897.00	824.00	809.00
56	996.00	916.50	945.00	953.50	760.00	955.50	968.00	927.50	960.50	1015.00	1000.50
70	873.50	702.00	846.50	815.50	725.00	874.00	857.50	787.00	876.50	887.00	909.50
94	865.50	701.00	595.00	759.50	700.50	751.00	804.50	685.50	789.00	857.50	775.50
	Biomass (kg/ha) of panicles										
94	2436.50	3596.50	3372.00	4776.50	4344.00	4004.50	4325.00	3835.50	4170.50	4439.50	3568.50

Yield components, such as the number of productive tillers per hill, the number of grains per (primary) panicle, the percentage of filled grains, the weight of 1000 grains, the total biomass per plant, and the grain yield were also significantly influenced by the time of nitrogen application (Table 6). Compared to the control treatment, application of nitrogen fertilizer 2 to 3 times within the period 0 to 42 DAT significantly increased the number of productive tillers by 15-30%. Nitrogen application later than 42 DAT did not significantly affect the number of productive tillers; it rather tended to reduce productive tiller number.

Nitrogen application also significantly affected the total number of grains per primary panicle, and the number of filled grains per primary panicle. In treatments T2, T4, T7, T10 and T11 the total number of grains per panicle increased by 21 to 35% compared to the control treatment, while the other five treatments did not differ significantly from the control treatment. The number of filled grains per panicle increased significantly as a result of N application in all treatments, except when nitrogen was applied at 70 and 84 DAT. The highest increase of filled grains was obtained in plots receiving nitrogen at 28 and 42 DAT (T2); 0, 14 and 28 DAT (T4); and 14, 28 and 42 DAT (T5). All treatments significantly increased the weight of 1000 grains as compared to the control treatment. The weight of grains obtained from fertilized plants was approximately 2% higher than that of unfertilized plants. (It must be noted that grain yields calculated from the yield component data given in Table 6 differ considerably from the harvested yields, because the yield components were determined on 10 primary panicles, not representing an average panicle.)

The above results are in agreement with reports by De Datta (1981), stating that high yields can be obtained during the dry season in the tropics without practicing a widely split N application. The high efficacy of early N application was also in accordance with Tanaka (1977), reporting that early maturing rice varieties have a distinct peak of N uptake at about 37 DAT.

N uptake, DS92 experiment

Table 7 lists the N contents of plant organs at various stages. Total crop N uptake is given in Figure 7. The final allocation of N to the various plant organs is depicted in Figure 8. This second experiment confirmed that early N application (28 and 42 DAT) had a significant effect on straw and grain nitrogen contents, also in the dry season; later N application did not result in significant effects on both traits.

Figure 9 shows that the filling of individual spikelets was independent of N application. Mean spikelet weight, determined from 10 random panicles, followed the same trajectory for plants that received no fertilizer N as for the plants that received 90 kg N/ha (two splits, at transplanting and panicle initiation) and 180 kg N/ha (four splits, at transplanting, active tillering, panicle initiation, and flowering). This confirms the observation that no source limitation existed during the grainfilling stage. The number of spikelets, not leaf area or leaf photosynthetic capacity (N content) during grain filing, determined final grain yield.

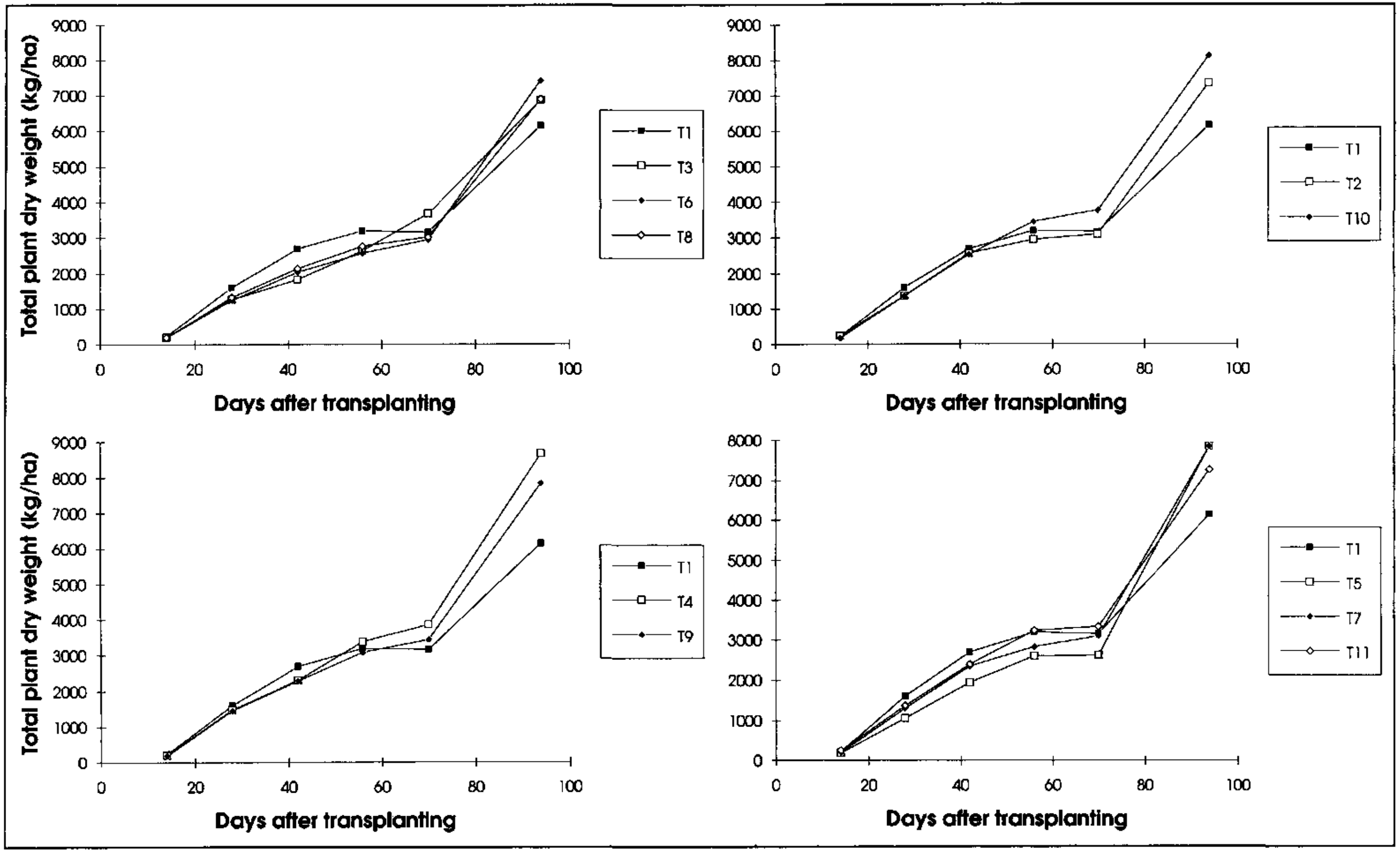

Figure 5a-5d. Effect of N application scheme on total crop biomass (incl. roots). Rice cvar IR64, 1992 dry season, Sukamandi, West Java. Treatment codes are explained in Table 1b.

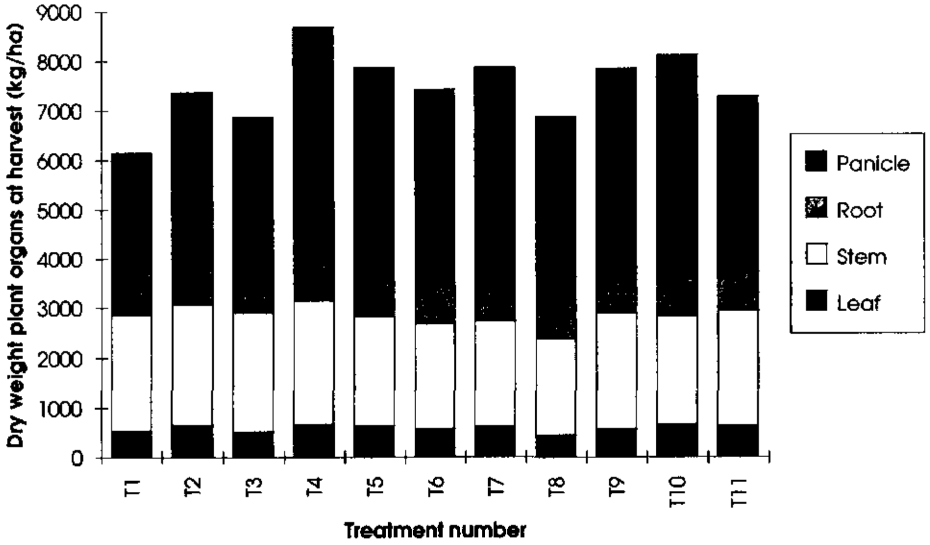

Figure 6. Effect of N application scheme on distribution of biomass at harvest. Rice cvar IR64, 1992 dry season, Sukamandi, West Java.

Table 6. Means of rice yield components observed in plots receiving split application of nitrogen, 1992 dry season, Sukamandi (Indonesia). Treatment codes are explained in Table 1b. Values marked with common letters are not significantly different according to Duncan's Multiple Range Test.

Treat-ment	Number of productive tillers per hill	Filled grains on prim. pinacle (%)	Number of grains per panicle on prim. panicle	1000 grains weight from prim. panicle (g)	Grains yield (t/ha)
T1	8.1 b	87.5 c	82.5 c	25.8 b	2.42 f
T2	10.8 a	90.9 ab	101.3 ab	26.5 a	3.57 de
T3	9.6 ab	88.8 bc	87.6 bc	26.3 a	3.32 e
T4	10.4 a	91.9 a	100.5 ab	26.4 a	4.67 a
T5	10.5 a	91.1 ab	93.2 bc	26.4 a	4.38 ab
T6	9.8 ab	91.7 a	95.8 bc	26.4 a	4.05 bcd
T7	9.5 ab	91.5 a	111.5 a	26.4 a	4.36 ab
T8	9.5 ab	91.8 a	97.7 bc	26.4 a	3.80 cde
T9	9.5 ab	92.3 a	111.1 a	26.5 a	4.16 bc
T10	9.9 ab	91.5 a	101.7 ab	26.4 a	4.47 ab
T11	9.9 ab	92.3 a	94.7 bc	26.3 a	3.53 e

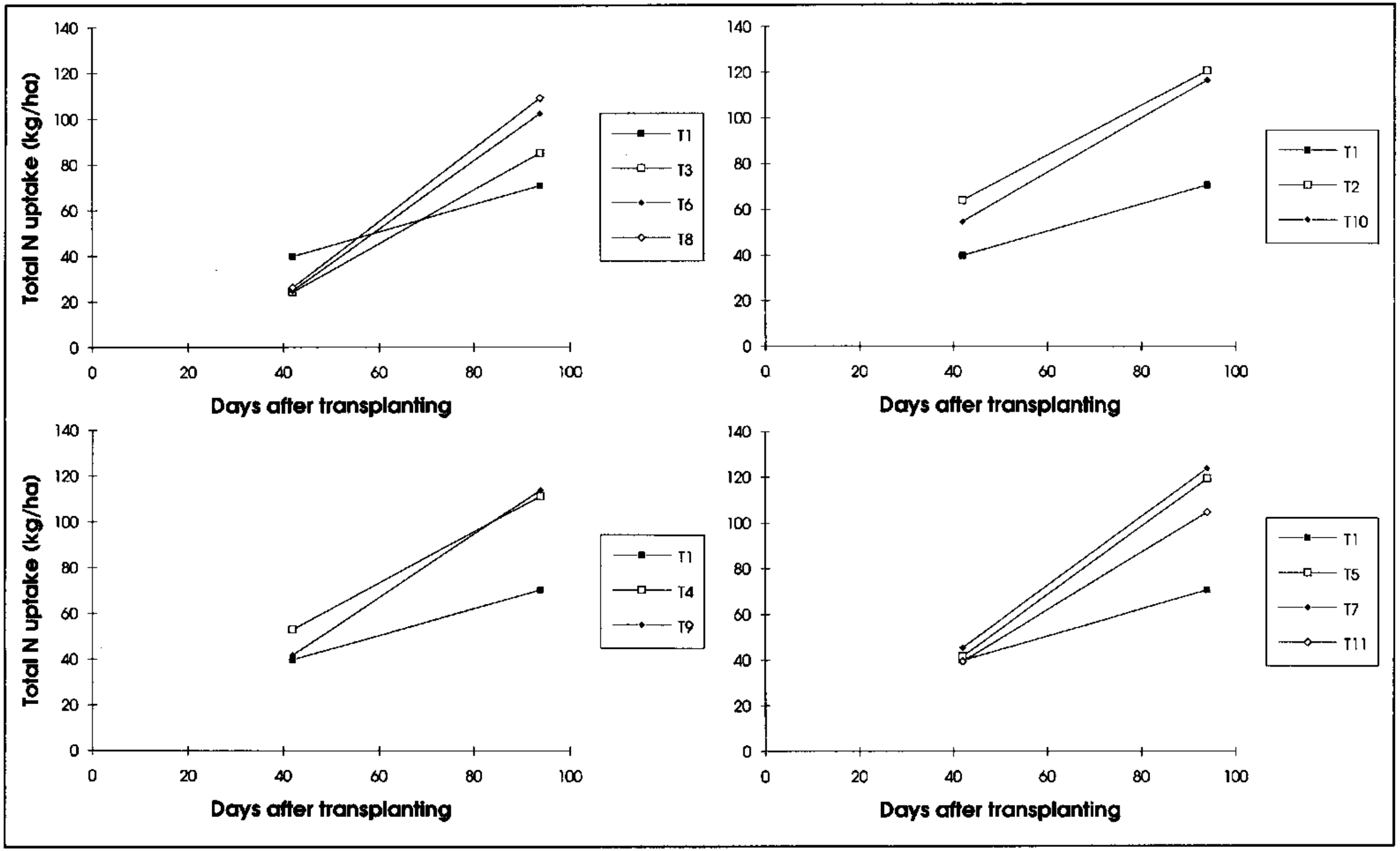

Figure 7a-7d. Effect of N application scheme on total N uptake by the crop. Rice cvar IR64, 1992 dry season, Sukamandi, West Java. Treatment codes are explained in Table 1b.

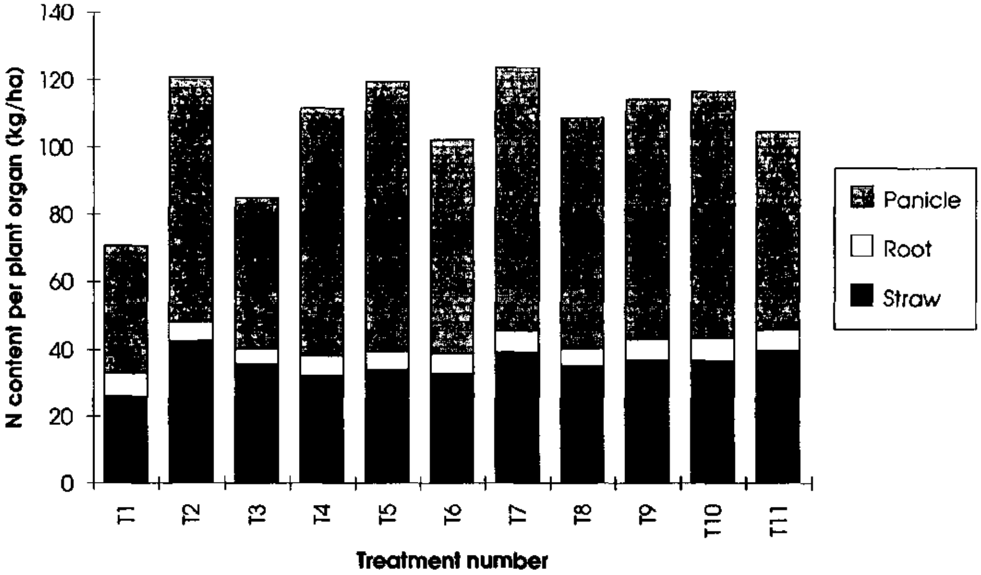

Figure 8. Effect of N application scheme on distribution of crop N at harvest. Rice cvar IR64, 1992 dry season, Sukamandi, West Java. Treatment codes are explained in Table 1b.

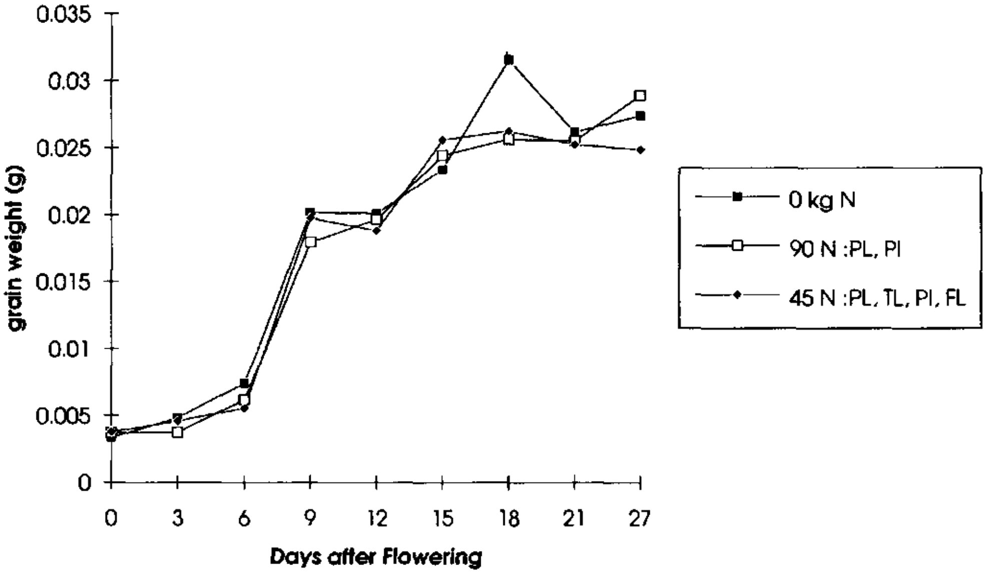

Figure 9. Spikelet filling in rice cvar IR64, in selected treatments of the 1992 dry season experiment, Sukamandi, West Java.

Table 7. Effect of N application dose and scheme on N contents of plant organs on various sampling dates. Rice cvar IR64, 1992 dry season, Sukamandi, West Java. Treatment codes are explained in Table 1b.

DAT	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
	N content (%) in straw										
42	1.82	3.07	1.65	2.76	2.88	1.49	2.47	1.5	2.49	2.81	2.07
94	0.91	1.39	1.22	1.02	1.2	1.22	1.43	1.47	1.27	1.29	1.35
	N content (%) in grains										
94	1.55	2.02	1.33	1.54	1.84	1.59	1.81	1.79	1.71	1.65	1.65

Conclusions

N fertilizer applied after panicle initiation was not efficiently used to increase grain yield and yield components. The best results were obtained when N was applied in 3 to 5 splits, with the first dressing no later than 28 DAT.

The highest grain yields in the wet season and the dry season crops were 4.97 t/ha and 4.67 t/ha, respectively. The wet season maximum was reached with 135 kg N/ha given at planting time; the best result in the dry season, where all treatments received 200 kg N/ha, was obtained with a three split application, at 0, 14 and 28 DAT.

The general observation in both experiments that post-panicle initiation uptake of available N was very low must be ascribed to either a low crop N demand at later stages - e.g. as a result of the low number of productive tillers and consequent limitation in sink size - or to the inability of the root system at later stages to acquire nitrogen from the soil system. At present, we cannot determine which of these hypotheses is valid. It is clear, however, that increasing late N uptake will have little or no effect on yield formation in the dry season. Increasing the number of productive tillers seems to be imperative to increase the yield level.

This set of experiments confirms that in the Sukamandi area, unlike at other rice growing sites, dry season yields and biomass production are lower than in the wet season. It has been suggested that the dry season weather conditions around flowering stage are responsible for the generally lower yields in this season. Our observations on spikelet number per panicle (primary panicles), grain filling, and the precentage of filled spikelets do not, however, confirm such a view. Nor could we detect any anomalies in the weather conditions during earlier (tillering) or later (grain filling) stages of crop development. We consider it more likely that a link exists between the generally (wet season and dry season) poor N uptake after 42 DAT on the one hand and the anomaly of lower dry season yields on the other. Careful analysis should reveal whether a limitation to root growth or functioning exists in this soil, which may be aggravated during the dry season. It is worthwhile to investigate in detail how soil management and soil conditions differ between wet and dry season, in order to devise the proper soil and crop management leading to yield levels closer to those permitted by the favorable weather conditions, particularly in the dry season.

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Nitrogen uptake capacity of irrigated lowland rice at different growth stages

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Abstract

A field experiment to determine the maximum nitrogen (N) uptake capacity of an irrigated lowland rice cultivar (IR72), was conducted in the Philippines in the 1993 dry season. The experiment consisted of 17 fertilizer-N treatments in different splits, ranging from 0 to 400 kg ha^{-1}. Envelope curves of maximum N content in leaves, stems, panicles and roots of IR72 throughout the crop cycle were derived. In one treatment, more than 100 kg N ha^{-1} was taken up by the plant after flowering. Grain yields (14% moisture) ranged from 4.8 to 10.7 t ha^{-1}. Postponing the first N application up until panicle initiation had no significant effect on grain yield. If N was applied for the first time at flowering, yields were the same as the 0 N plots (i.e. 5 tons ha^{-1}) but the percentage of N in the grains increased from 0.87% to 1.75%. Yields increased linearly with crop N status between panicle initiation and flowering, but remained constant if the crop N content exceeded 80 kg N/ha. The filled grains percentage ranged from 80 - 94%. High N inputs resulted in a larger number of panicles per hill, a greater number of spikelets per panicle and a lower percentage of filled grains. Yield differences among treatments were mainly due to differences in number of panicles per m^2 and number of spikelets per panicle and were largely determined by crop N status in the period between panicle initiation and flowering. The percentage of unfilled grains per panicle increased at higher N application levels, possibly due to spikelet sterility problems.

Introduction

A very important yield determining factor for irrigated rice is the nitrogen uptake capacity of the plant. The concentration of nitrogen in the leaves, especially in the higher part of the canopy, plays an important role in photosynthesis and, therefore, crop growth. Moreover, at a later growth stage, a percentage of leaf and stem nitrogen is translocated to the grains.

Recent experimental results obtained at the International Rice Research Institute (IRRI), Philippines show evidence for a decline in soil-N supplying capacity under intensively cropped irrigated rice systems (Cassman et al., 1993). In the late 1960's, average irrigated rice yield in continuously cropped long-term experiments in the dry season at IRRI was 9-10 tons ha^{-1}. In the 1980's yields had dropped to a low 6-7 tons ha^{-1}. Simulation modelling analyses predicted that with increased leaf nitrogen contents, yields could be brought back to 9-10 tons ha^{-1} in the dry season. Field experiments conducted afterwards, indeed confirmed that with higher nitrogen inputs, the decline in yield could be reversed (Kropff et al., 1993a, b).

To optimize nitrogen application, a thorough understanding of the mechanisms of N losses, N uptake, N distribution within the plant, and the impact of plant N content on crop growth and yield is needed. The maximum N uptake capacity of irrigated rice at any time will determine the yield plateau of the crop, if no other factors are limiting or reducing crop growth. Such information is also crucial for modelling the N distribution in the plant (Drenth and Ten Berge, 1993).

A field experiment was conducted to quantify the maximum N uptake capacity at any growth stage of an improved short straw, medium duration rice cultivar under fully irrigated conditions. The impact of crop N content on crop growth and grain yield was investigated.

Materials and methods

Field site and treatments

The field experiment was conducted at the International Rice Research Institute (IRRI), Philippines (14°30'N, 121°15'E). The soil was classified as a mixed, isohyperthermic Typic Tropudalf (Soil Survey Staff, 1975). An improved semi-dwarf Indica rice cultivar (IR72) was grown in the non-monsoon season on a 5000 m^2 experimental field, under irrigated conditions from 14 January (transplanting date) to 30 April 1993 (last harvest date). To homogenize the field, IR72 was also grown in the monsoon season of 1992, with fertilizer input according to standard IRRI recommendations. Prior to transplanting (3 seedlings per hill, 21 days old seedlings, 20 × 20 cm spacing), the soil was plowed and harrowed two times under water-saturated conditions. The field was divided into 56 subplots of 6.6 m × 11.0 m, which remained flooded throughout the experiment. P and K fertilizer were applied 2 days before transplanting (40 kg P ha^{-1} and 40 kg K ha^{-1}). The timing and amount of N fertilizer as urea was an experimental treatment. Total nitrogen input ranged from 0 to 400 kg N ha^{-1}. Initial number of treatments was 14 (T0 - T13). Timing corresponded to a phenological scale. The number of splits ranged from 0 (control plots) to 7 (i.e. at transplanting, 2 weeks after transplanting, mid-tillering, panicle initiation, in between panicle initiation and flowering, flowering and 1 week after flowering). Treatments were assigned to subplots according to a complete randomized block design, with four replications. For three treatments (T1, T2, T3), the effect of the last application (at one week after flowering) was investigated. For this purpose, subplots were divided into two equal parts using a plastic sheet that was pushed down into the puddled soil using a wooden plank. N was not applied to one half of the plot, yielding three additional treatments (T1-, T2- and T3-). An overview of all treatments (17) is given in Table 1.

Table 1. Overview of timing and rate of N application for the various treatments in the field experiment. TR= transplanting, TR+2 = two weeks after transplanting, MT = mid-tillering, PI = panicle initiation, PI-F = half way panicle initiation and flowering, F = flowering, F + 1 wk = one week after flowering.

Treatment	TR	TR + 2wks	MT	PI	PI-F	F	F + 1wk	Total
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
T0	0	0	0	0	0	0	0	0
T1+	0	0	0	0	0	150	150	300
T2+	0	0	0	0	100	100	100	300
T3+	0	0	0	75	75	75	75	300
T4	0	0	60	60	60	60	60	300
T5	0	50	50	50	50	50	50	300
T6	43	43	43	43	43	43	43	300
T7	150	150	0	0	0	0	0	300
T8	75	75	75	75	0	0	0	300
T9	50	50	50	50	50	50	0	300
T10	7.1	7.1	7.1	7.1	7.1	7.1	7.1	50
T11	14.3	14.3	14.3	14.3	14.3	14.3	14.3	100
T12	28.6	28.6	28.6	28.6	28.6	28.6	28.6	200
T13	57.1	57.1	57.1	57.1	57.1	57.1	57.1	400
T1-	0	0	0	0	0	150	0	150
T2-	0	0	0	0	100	100	0	200
T3-	0	0	0	75	75	75	0	225

Crop and weather measurements

The above ground biomass of 12 hills was sampled in every subplot one day before every fertilizer application and at physiological maturity (defined as the date at which the lower portion of the youngest effective panicles turn yellow). The T0 plots were included in every sampling; these data were considered to be representative for subplots that received N at a later stage only (e.g. T1, T2, T3) up to the moment of fertilizer application in these plots. Leaf area index of green leaves and flag leaves (LAI) was determined for a subsample of six hills. Total dry matter of leaves, stems, panicles (dried at 80°C during two days) was determined for all 12 hills. During the first sampling (2 weeks after transplanting) 24 hills were sampled, and a subsample of 12 hills was used to determine LAI. At every sampling total dry matter of roots was determined for 4 hills only, down to a depth of 20 cm. After determination of dry mass, samples were ground and the N content of plant organs (i.e. green, dead and flag leaves, and stems, panicles and roots) was determined using the micro-Kjeldahl method. Final yield at harvest was determined for a sampling area of 5.2 m^2 per plot; a yield component analysis was conducted for 6 hills per plot. Weather variables (i.e. global radiation, minimum and maximum air temperature) were recorded at a meteorological station located within 200 m from the experimental field. Adequate crop protection measures were taken throughout the experiment.

N uptake

The maximum N content per plant organ at any time was determined by comparing N contents across treatments during the complete crop cycle. The resulting 'envelope curve' is an important input parameter for the simulation model ORYZA-N (Drenth and Ten Berge, 1993), which assumes that plant organs can take up N to a preset maximum limit. For panicle N content this maximum is assumed to be constant over time.

Results and discussion

Maximum tillering and panicle initiation occurred roughly at the same time for all treatments, i.e. around 30 days and 42 days after transplanting (DAT) respectively. Application of fertilizer postponed flowering, physiological maturity and final harvest. The strongest effect on development was observed in the T3 and T2 treatments, which received N for the first time at panicle initiation, and between panicle initiation and flowering respectively. Application of fertilizer-N decreased the development rate in the reproductive phase, i.e. increased the grainfilling period (Table 2).

Dry mass of the total crop increased for all treatments over time (Figure 1). Green leaf dry mass (including flag leaves) increased for all treatments during the vegetative phase, and started decreasing from flowering onwards, coinciding with an increase in dead leaf dry mass (Table 3). For the T1 and T2 treatments a slight increase in leaf dry mass after flowering was observed, resulting in an increase in LAI (Figure 2). Stem dry mass increased steadily up to flowering and remained more or less constant afterwards (Table 3). Translocation of carbohydrates from the stem to the grains was therefore relatively unimportant. Differences in dry mass of green leaves, dead leaves, flag leaves and stems at a particular day after transplanting between treatments were large. In both T2+ and T2- plots, a large number of 'extra' flowering tillers appeared about 20 days after first flowering which were not reproductive. Observations of root dry mass were done up until flowering only. Weights increased at a more or less constant rate with time. Root weights were remarkably similar among treatments and ranged from 750 (T0) to 1030 kg ha^{-1} (T10) at flowering.

The nitrogen concentration in the green leaves and in the stem were largest shortly after transplanting and decreased continuously over time (Table 4). A rapid decline was observed between panicle initiation and flowering. The concentration in dead leaves differed among treatments but remained more or less constant. The nitrogen concentration of the flag leaves was substantially higher than that of the green leaves, and decreased steadily after emergence (Table 4). Differences among treatments were large. The nitrogen concentration in the roots was relatively low and also showed some difference among treatments.

Table 2. Phenological events per treatment observed in the field experiment. Treatment codes are explained in Table 1. DAT = days after transplanting. Date of flowering is date when 50% of panicles are flowering. DVRV, DVRR = development rate in vegetative and reproductive phase resp.

Treatment	Flowering	Physiological maturity	Harvest	DVRV	DVRR
	(DAT)	(DAT)	(DAT)	(°Cd)$^{-1}$	(°Cd)$^{-1}$
T0	69	90	96	0.000699	0.002521
T1+, T1-	70	96	102	0.000690	0.002005
T2+, T2-	71	101	106	0.000682	0.001716
T3+, T3-	73	101	106	0.000666	0.001829
T4	72	100	105	0.000674	0.001835
T5	70	100	105	0.000690	0.001723
T6	71	99	103	0.000682	0.001843
T7	72	95	101	0.000674	0.002262
T8	70	96	102	0.000690	0.002005
T9	70	98	103	0.000690	0.001852
T10	69	93	98	0.000699	0.002196
T11	69	94	100	0.000699	0.002102
T12	70	95	101	0.000690	0.002094
T13	70	99	103	0.000690	0.001785

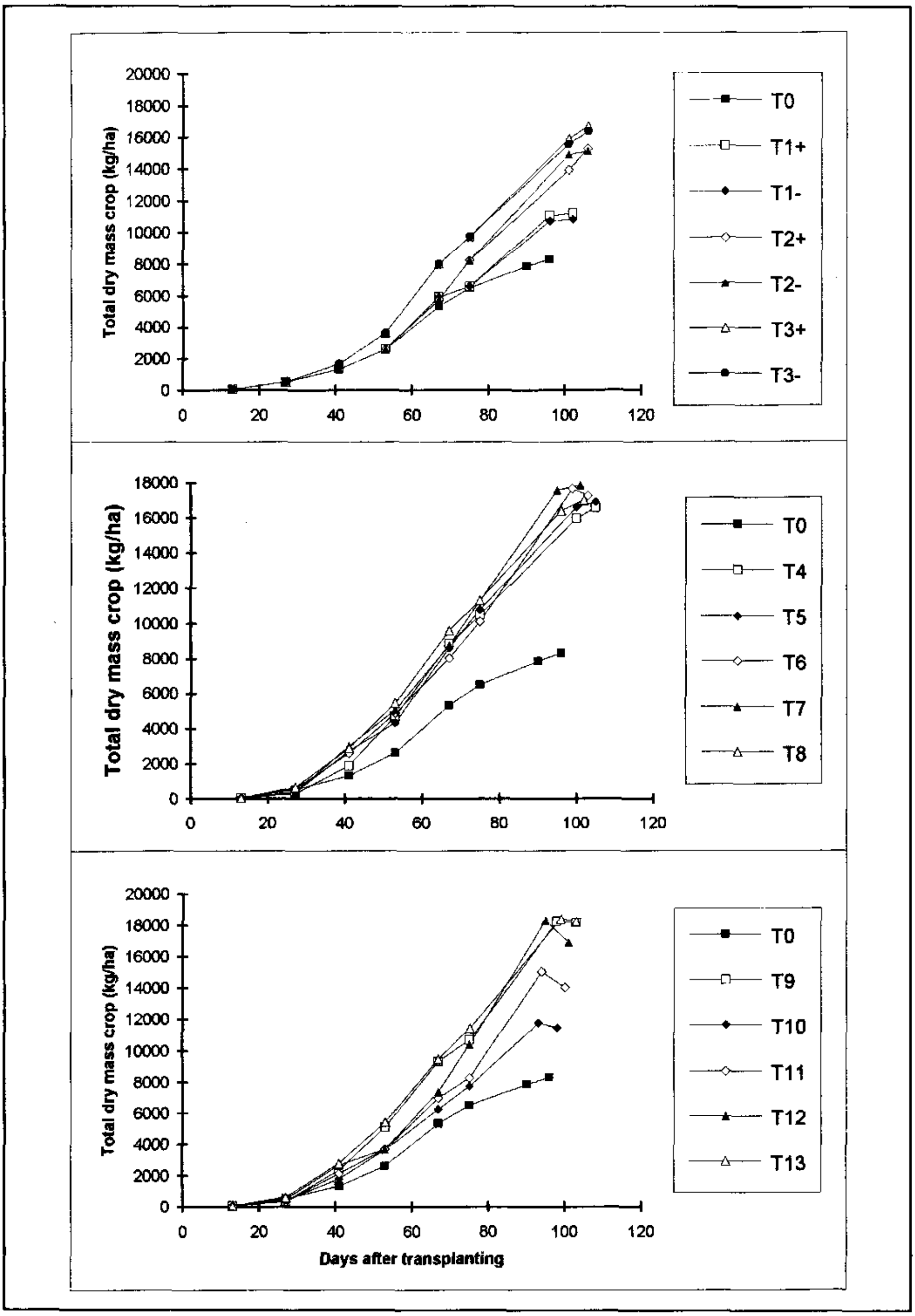

Figure 1. Dry mass of the total crop as a function of days after transplanting for cv. IR72 in the field experiment. Treatment codes are explained in Table 1.

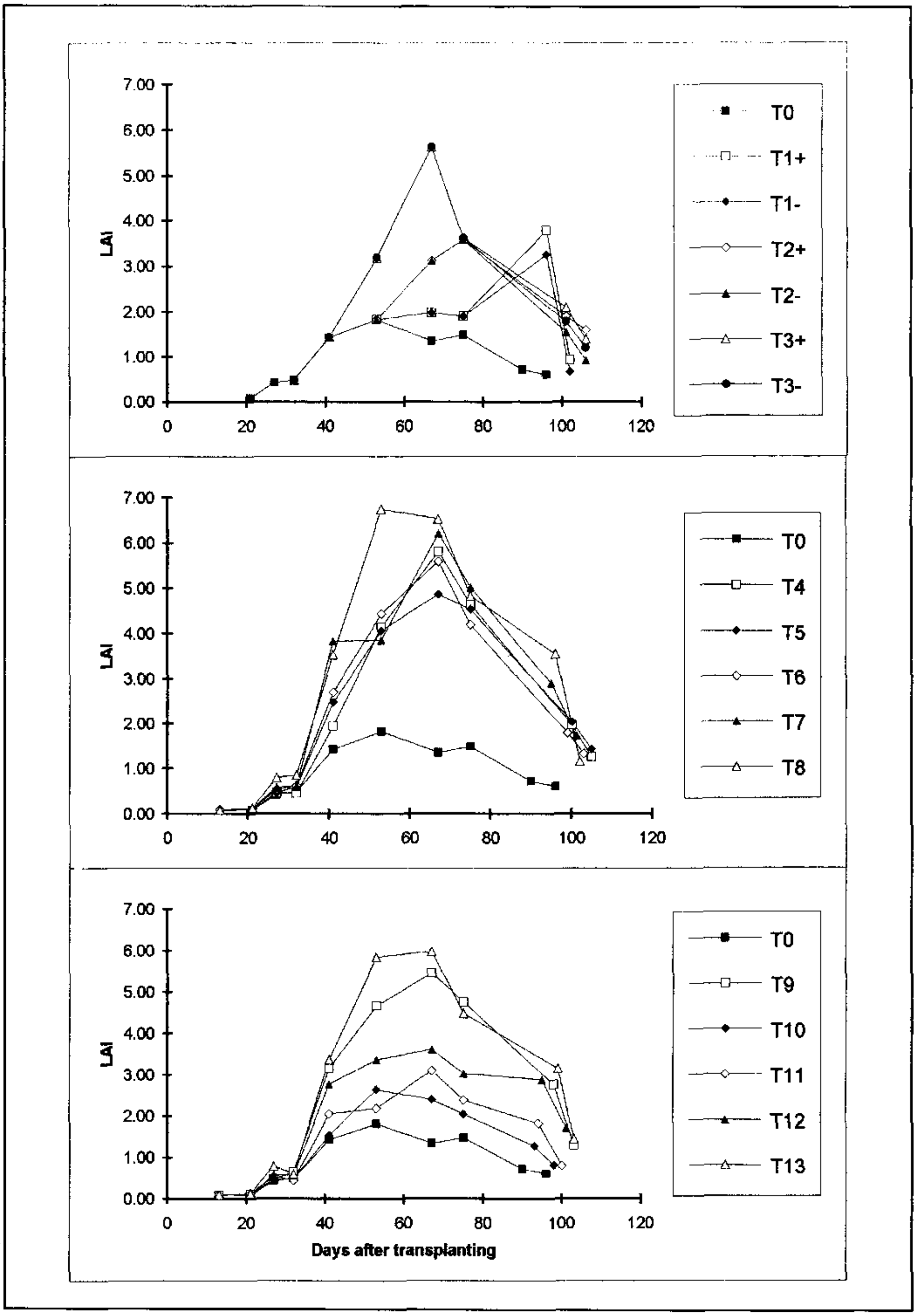

Figure 2. LAI of cv. IR72 as a function of days after transplanting in the field experiment. Treatment codes are explained in Table 1.

Table 3. Dry mass of plant organs as a function of days after transplanting (DAT) for cv. IR72 in the field experiment. Treatment codes are explained in Table 1. GLDM = Dry mass of green leaves (excluding flag leaves), DLDM = dry mass of dead leaves, SDM = dry mass of stems, PDM = dry mass of panicles, RDM = dry mass of rachis, GDM = dry mass of grains (corrected to 3% moisture content), FLDM = dry mass of flag leaves, RTDM = dry mass of roots.

Treatment		GLDM	DLDM	SDM	PDM	RDM	GDM	FLDM	RTDM
	DAT	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)
T0	13	33		32					
T0	27	166	185	122					70
T0	41	529		655					156
T0	53	896		1449					272
T0	67	624	220	2648	854			244	753
T0	75	775	369	2812	1840			212	500
T0	90	294	500	2281	4106	259	3847	186	500
T0	96	294	500	2281	4570	259	4311	186	500
T1+	67	951	152	2976	886			211	772
T1+	75	818	249	2527	2073			225	700
T1+	96	1126	211	3787	4927	418	4509	333	700
T1+	102	1126	211	3787	5044	418	4626	333	700
T1-	96	930	390	3630	4718	454	4264	370	700
T1-	102	930	390	3630	4819	454	4365	370	700
T2+	67	1291	74	2608	873			205	731
T2+	75	1474	217	3341	2123			288	800
T2+	101	852	773	3624	7271	1121	6150	615	800
T2+	106	852	773	3624	8618	1121	7497	615	800
T2-	101	650	805	3600	8552	1082	6723	514	800
T2-	106	650	805	3600	8777	1082	7695	514	800
T3+	41	593		771					313
T3+	53	1483		1763					378
T3+	67	2149	152	3544	998			471	722
T3+	75	1636	317	3816	2615			488	897
T3+	101	664	1093	3924	8427	556	7870	910	900
T3+	106	664	1093	3924	9250	556	8694	910	900
T3-	101	566	1147	3868	8333	528	7805	747	900
T3-	106	566	1147	3868	9175	526	8649	747	900

Table 3 continued next page

Table 3 continued

Treatment		GLDM	DLDM	SDM	PDM	RDM	GDM	FLDM	RTDM
	DAT	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)
T4	13	33		32					
T4	27	156		151					
T4	41	797		774					309
T4	53	1914		2326					475
T4	67	2115	165	3977	1405			478	694
T4	75	1925	234	4068	2586			737	941
T4	100	520	1300	3799	8827	516	8311	587	940
T4	105	520	1300	3799	9408	516	8892	623	940
T5	13	29		26					
T5	27	158	157	93					
T5	41	1009		936					763
T5	53	1855		2099					397
T5	67	2330	231	3713	1232			455	672
T5	75	1863	279	4473	2846			508	831
T5	100	675	1201	4190	9108	596	8511	618	831
T5	105	675	1201	4190	9326	596	8730	665	831
T6	13	35		35					
T6	27	207	206	171					
T6	41	1115		1062					431
T6	53	2106		2375					406
T6	67	2109	198	3645	908			344	828
T6	75	1721	398	3658	3003			524	809
T6	99	757	1394	4298	9780	573	9206	637	809
T6	103	757	1394	4298	9375	573	8802	637	809
T7	13	28		26					
T7	27	205		204					
T7	41	1294		1074					625
T7	53	2321		2353					409
T7	67	2222	299	4205	935			498	591
T7	75	1744	616	5070	2461			522	881
T7	95	966	1383	5600	8143	523	7621	593	881
T7	101	966	1383	5600	8425	523	7902	593	881

Table 3 continued next page

Table 3 continued

Treatment		GLDM	DLDM	SDM	PDM	RDM	GDM	FLDM	RTDM
	DAT	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)
T8	13	31		31					
T8	27	248	232	189					
T8	41	1332		1118					447
T8	53	2708		2355					428
T8	67	2307	363	4513	1172			511	731
T8	75	1687	792	4602	2790			680	772
T8	96	853	1672	4019	8363	535	7828	732	772
T8	102	853	1672	4019	8951	563	8388	732	772
T9	13	33		32					
T9	27	180		169					
T9	41	1102		1019					266
T9	53	2255		2402					472
T9	67	2038	233	4304	1461			479	803
T9	75	1882	394	4215	2825			531	853
T9	98	856	1299	4829	9699	594	9105	708	853
T9	103	856	1299	4829	9639	594	9045	708	853
T10	13	41		40					
T10	27	160	102	136					
T10	41	662		803					353
T10	53	1212		1918					544
T10	67	1010	159	3179	912			204	813
T10	75	870	425	2735	2417			263	1031
T10	93	443	773	3096	6146	369	5777	288	1031
T10	98	443	773	3096	5823	369	5454	288	1031
T11	13	33		30					
T11	27	183		173					
T11	41	758		845					559
T11	53	1358		1923					434
T11	67	1182	171	3414	1008			275	950
T11	75	983	378	3376	2375			288	884
T11	94	688	776	4560	7735	465	7270	419	884
T11	100	688	776	4560	6711	465	6246	419	884

Table 3 continued next page

Table 3 continued

Treatment		GLDM	DLDM	SDM	PDM	RDM	GDM	FLDM	RTDM
	DAT	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)
T12	13	36		33					
T12	27	183	158	165					
T12	41	985		1048					669
T12	53	1587		1779					322
T12	67	1336	271	3529	1143			309	819
T12	75	1261	437	3969	3476			393	853
T12	95	1033	939	5348	9522	539	8983	625	853
T12	101	1033	939	5348	8135	539	7596	625	853
T13	13	33		32					
T13	27	226	255	151					
T13	41	1183		1135					509
T13	53	2456		2520					472
T13	67	2400	199	4154	1367			532	828
T13	75	1805	541	4228	3321			599	931
T13	99	1172	1374	4615	9519	633	8886	806	931
T13	103	1172	1374	4615	9336	633	8703	806	931

Table 4. N concentration in plant organs as a function of days after transplanting (DAT) for cv. IR72 in the field experiment. Treatment codes are explained in Table 1. NCGL = Nitrogen concentration of green leaves (excluding flag leaves), NCDL = nitrogen concentration of dead leaves, NCS = nitrogen concentration of stems, NCP = nitrogen concentration of panicles, NCFL = nitrogen concentration of flag leaves, NCR = nitrogen concentration of roots.

Treatment	DAT	NCGL	NCDL	NCS	NCP	NCFL	NCR
		%	%	%	%	%	%
T0	13	4.09		2.17			1.48
T0	27	4.10	0.60	2.14			1.59
T0	41	2.96		1.43			1.24
T0	53	2.40		0.87			0.84
T0	67	1.42	0.62	0.54	0.87	2.18	0.48
T0	75	1.29	0.53	0.50	0.87	2.27	0.60
T0	90	1.02	0.43	0.40	0.87	1.17	0.39
T0	96	1.08	0.43	0.41	0.87	1.48	0.43

Table 4 continued next page

Table 4 continued

Treatment	DAT	NCGL	NCDL	NCS	NCP	NCFL	NCR
		%	%	%	%	%	%
T1+	67	1.42	0.57	0.54	1.44	2.30	0.49
T1+	75	1.99	0.68	0.99	1.44	2.82	0.63
T1+	96	1.98	0.70	0.90	1.44	1.97	0.54
T1+	102	1.93	1.01	0.84	1.83	1.54	0.69
T1-	96	1.98	0.70	0.73	1.44	1.97	0.50
T1-	102	1.61	0.93	0.73	1.74	1.10	0.68
T2+	67	2.47	0.86	1.43	1.92	3.09	0.59
T2+	75	2.55	1.09	1.38	1.92	2.68	0.65
T2+	101	1.95	1.13	1.13	1.92	1.65	0.68
T2+	106	1.90	1.10	1.00	1.75	1.82	0.67
T2-	101	1.69	0.84	0.91	1.61	1.36	0.62
T2-	106	1.50	0.80	0.75	1.50	1.30	0.60
T3+	41	2.87		1.45			1.19
T3+	53	3.43		1.61			1.47
T3+	67	2.72	1.21	1.27	1.56	3.11	0.61
T3+	75	2.48	1.07	1.11	1.56	2.95	0.88
T3+	101	1.62	1.14	0.92	1.56	1.33	0.70
T3+	106	1.45	0.86	0.75	1.49	1.37	0.67
T3-	101	1.74	1.05	0.85	1.48	1.60	0.78
T3-	106	1.23	0.76	0.69	1.33	1.25	0.65
T4	13	4.09		2.17			1.48
T4	27	4.00		1.83			1.64
T4	41	3.58		1.93			1.69
T4	53	3.63		1.52			1.29
T4	67	2.53	1.06	1.21	1.33	2.89	0.64
T4	75	2.44	1.07	1.12	1.33	2.95	0.71
T4	100	1.05	0.89	0.91	1.33	1.02	0.86
T4	105	1.26	0.89	0.71	1.43	1.06	0.70
T5	13	4.08		2.30			1.65
T5	27	4.47		2.49			1.70
T5	41	3.53		1.90			1.50
T5	53	3.63		1.50			0.95

Table 4 continued next page

Table 4 continued

Treatment	DAT	NCGL	NCDL	NCS	NCP	NCFL	NCR
		%	%	%	%	%	%
T5	67	2.29	1.03	0.95	1.48	2.80	0.61
T5	75	2.35	1.03	1.08	1.48	2.95	0.67
T5	100	1.44	0.81	0.70	1.48	1.30	0.40
T5	105	1.17	0.89	0.76	1.58	1.05	0.80
T6	13	4.12		2.14			1.37
T6	27	4.24		2.22			1.55
T6	41	3.54		2.23			1.35
T6	53	3.29		1.38			1.01
T6	67	2.18	1.01	1.01	1.42	2.49	0.66
T6	75	2.31	1.04	1.06	1.42	2.83	0.69
T6	99	1.64	0.85	0.85	1.42	1.28	0.64
T6	103	1.23	0.91	0.83	1.50	0.90	0.77
T7	13	4.09		2.26			1.58
T7	27	4.40		2.46			1.77
T7	41	3.83		2.61			1.98
T7	53	3.50		1.67			0.85
T7	67	2.05	0.78	0.82	1.04	2.39	0.73
T7	75	1.96	0.78	0.79	1.04	2.71	0.70
T7	95	1.65	0.64	0.48	1.04	1.82	0.59
T7	101	0.69	0.64	0.52	1.04	0.75	0.52
T8	13	4.20		2.37			1.42
T8	27	4.55		2.41			1.60
T8	41	4.17		2.36			1.46
T8	53	3.93		2.58			1.62
T8	67	2.17	0.94	0.87	1.11	2.50	0.64
T8	75	2.03	0.95	0.95	1.11	2.68	0.73
T8	96	1.41	0.73	0.56	1.11	1.81	0.65
T8	102	0.75	0.75	0.63	1.21	1.17	0.80
T9	13	4.19		2.38			1.63
T9	27	4.39		2.20			1.75
T9	41	3.63		2.11			1.43
T9	53	3.37		1.87			1.46
T9	67	2.47	0.78	0.97	1.36	2.79	0.55

Table 4 continued next page

Table 4 continued

Treatment	DAT	NCGL	NCDL	NCS	NCP	NCFL	NCR
		%	%	%	%	%	%
T9	75	2.37	1.06	1.12	1.36	2.99	0.68
T9	98	1.56	0.85	0.65	1.36	1.79	0.56
T9	103	1.29	0.79	0.65	1.37	0.89	0.76
T10	13	4.10		2.24			1.26
T10	27	4.03		2.10			1.80
T10	41	2.64		1.45			1.40
T10	53	2.64		0.99			0.75
T10	67	1.44	0.57	0.64	1.00	2.31	0.53
T10	75	1.38	0.55	0.58	1.00	2.25	0.50
T10	93	1.25	0.52	0.54	1.00	1.89	0.45
T10	98	1.21	0.53	0.55	0.99	1.15	0.37
T11	13	3.90		2.05			1.45
T11	27	4.17		2.18			1.61
T11	41	3.28		1.76			1.41
T11	53	3.16		1.12			0.83
T11	67	1.79	0.84	0.68	1.15	2.38	0.56
T11	75	1.65	0.66	0.64	1.15	2.60	0.53
T11	94	1.00	0.48	0.55	1.15	1.61	0.34
T11	100	0.89	0.54	0.60	1.15	0.79	0.52
T12	13	4.04		1.52			1.39
T12	27	4.48		2.34			2.43
T12	41	3.09		1.97			1.95
T12	53	3.27		1.40			1.11
T12	67	1.92	0.86	0.82	1.42	2.60	0.51
T12	75	1.74	0.75	0.82	1.42	2.57	0.56
T12	95	2.06	0.69	0.60	1.42	2.01	0.58
T12	101	0.96	0.70	0.62	1.42	0.86	0.55
T13	13	4.04		2.29			1.61
T13	27	4.54		2.29			2.40
T13	41	3.95		2.08			1.51
T13	53	3.71		1.55			1.16
T13	67	2.58	1.25	1.10	1.61	3.00	0.70
T13	75	2.34	1.09	1.26	1.61	2.88	0.75
T13	99	2.53	1.31	0.96	1.61	1.89	0.74
T13	103	1.60	1.00	0.87	1.56	1.08	0.88

The maximum N% per plant organ at any time during the experiment is plotted in Figure 3a. This 'envelope curve' consists of data from various treatments and it determines the maximum N-uptake in a crop cycle. For reference, the minimum N concentrations as observed in the zero N plots are shown in Figure 3b. Comparison between both figures shows the potential increase in N content through fertilizer application. The maximum N content of the green leaves varied from 4.55%, two weeks after transplanting (T8, T13), to 1.90% at harvest (T2+). The maximum flag leaf N content was observed just before flowering (3.11%, T3). Maximum flag leaf N content at harvest was 1.82% (T2+). The maximum N content of the stem was 2.61% (T7 at panicle initiation), and at harvest 1.0% (T2+). The maximum N content of roots was 2.43% (T12, mid-tillering). Maximum N content at harvest was 0.88% (T13). Maximum N content of dead leaves was 1.31% (T13, at physiological maturity), at harvest 1.10% (T2+). Late application of N resulted in high N contents in all plant organs including the panicle. The N content in the T0 plots of the panicle was low: 0.87%. Application of N at flowering increased this percentage to 1.83% at harvest for T1+ and 1.74% at harvest for T1-. Application of N at panicle initiation resulted in a grain N% of 1.92 (T2+) at maturity and 1.75 (T2+) at harvest. Results show that the N% of the grains can be increased rather easily, even if the N status of the plant in the vegetative phase is low.

The N uptake for the total crop is shown in Figure 4. For T1+, total crop N increased substantially after application (Figure 4a) but this had no result on final yield (5.2 t ha^{-1} compared with 4.8 t ha^{-1} for T0). The 'sink size' for grain carbohydrates is determined between panicle initiation and flowering, i.e. before the first application in T1. The only effect was an increase in N% in the grains (1.83% versus 0.87% for T0). Differences between T1+ and T1-, T2+ and T2- and T3+ and T3- were negligible, indicating that N applied 1 week after flowering had no additional beneficial effect.

Total N uptake of treatments T4, T5, T6, T7 and T8 (Figure 4b) and final grain yield (Table 5) were quite similar. Comparison with results obtained for T3 shows that postponing the first N application up until panicle initiation had no effect on final yield and resulted in a relatively low dry mass of leaves and stems compared with panicle dry mass, and thus a relatively high harvest index (Table 5). A relatively low harvest index was obtained for T7, because of rapid growth in the vegetative stage.

N uptake after flowering was very pronounced in most treatments. An extreme case was T2+, with 112 kg N/ha uptake after flowering, i.e. roughly 3 kg N day^{-1}. Total N uptake for the zero N plots over the complete crop cycle was about 60 kg N ha^{-1}. Recovery percentages were very variable, ranging from 27% (T7) to 64% (T2-, T10, T11), see Table 5. A good linear relationship between leaf N and total plant N in the vegetative stage was found (Figure 5).

Calculated yields from yield components of 6 hills sampled at harvest and 5.2m^2 harvest area yield agreed reasonably well (Table 6). High N input levels resulted in a larger number of spikelets per panicle, a greater number of panicles per hill but a lower percentage of filled spikelets per panicle (Table 6). Differences in yield were mainly due to differences in sink size, i.e. number of panicles per m^2 and number of spikelets per panicle.

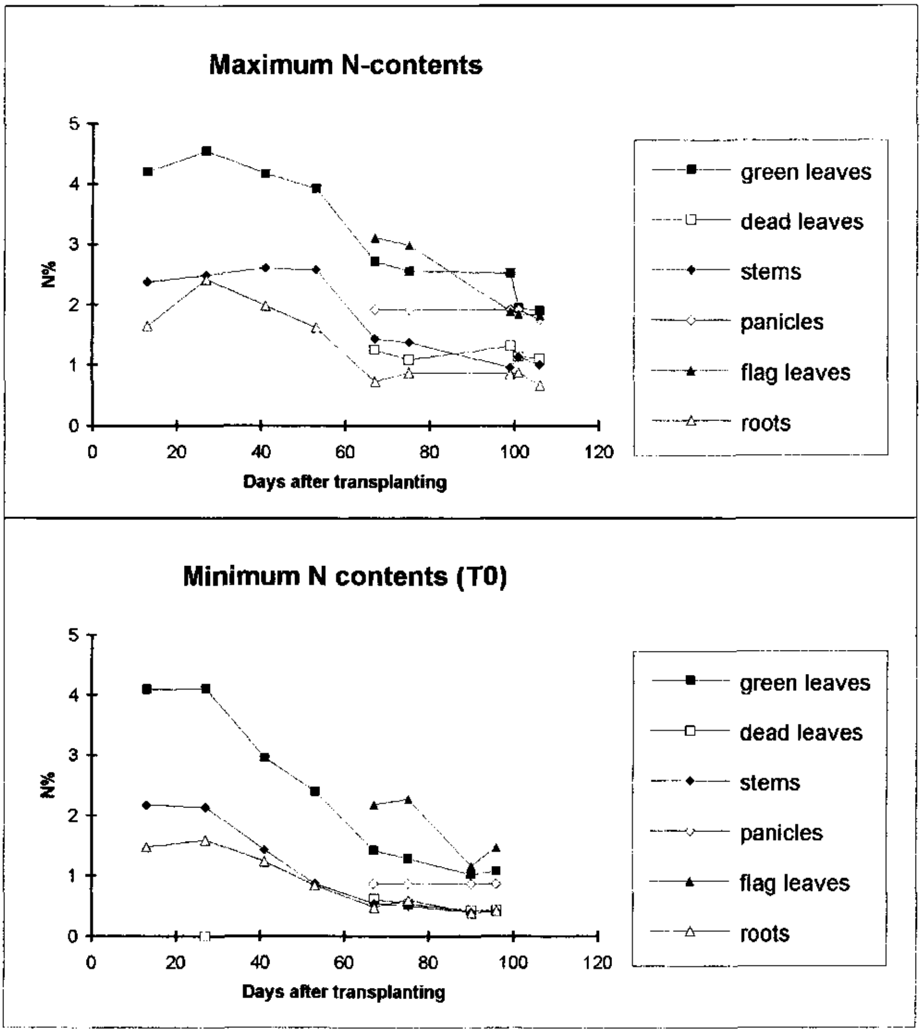

Figure 3. Maximum and minimum N concentration in plant organs as a function of days after transplanting for cv. IR72 in the field experiment. Treatment codes are explained in Table 1.

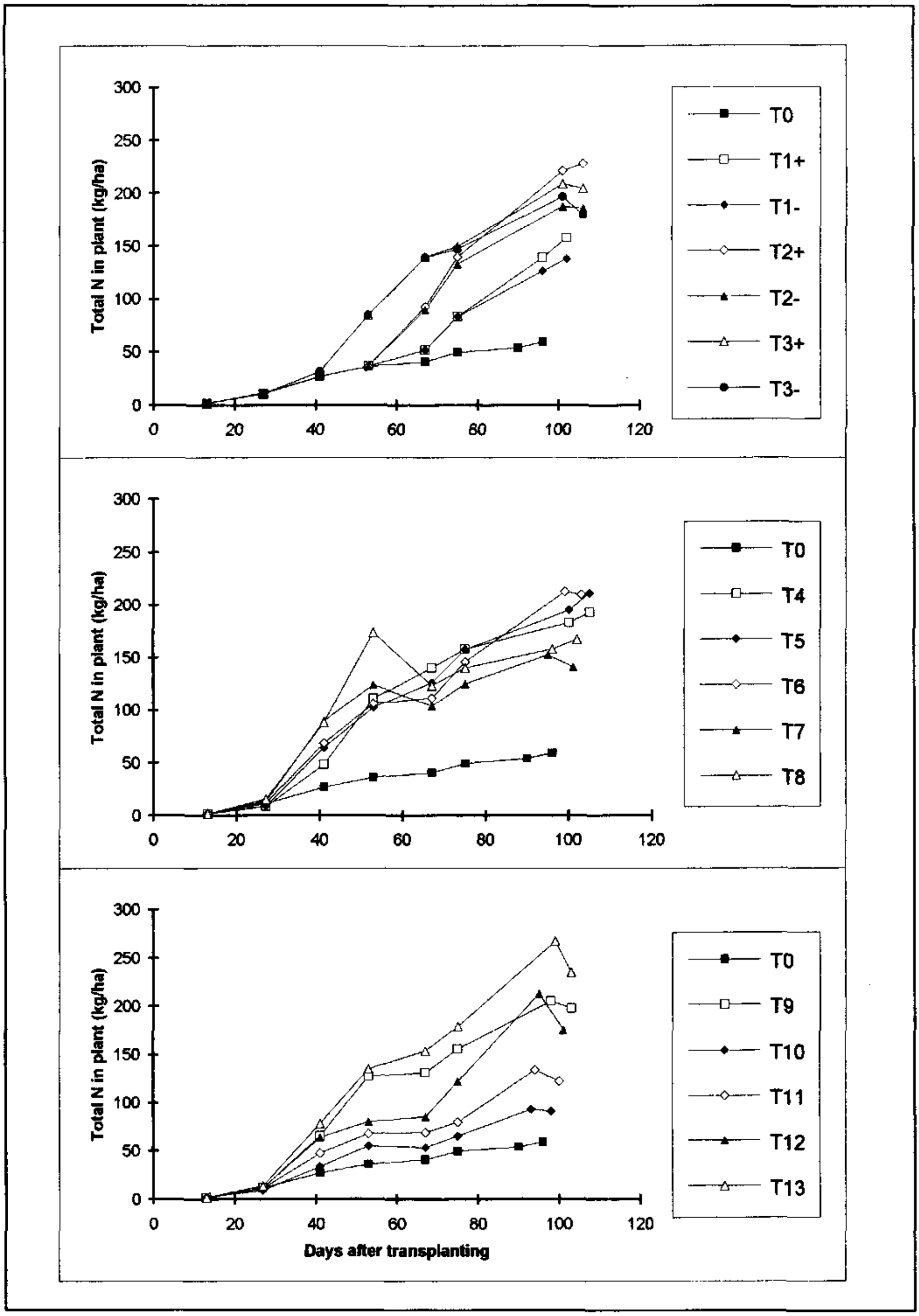

Figure 4. Total N in crop as a function of days after transplanting. Treatment codes are explained in Table 1.

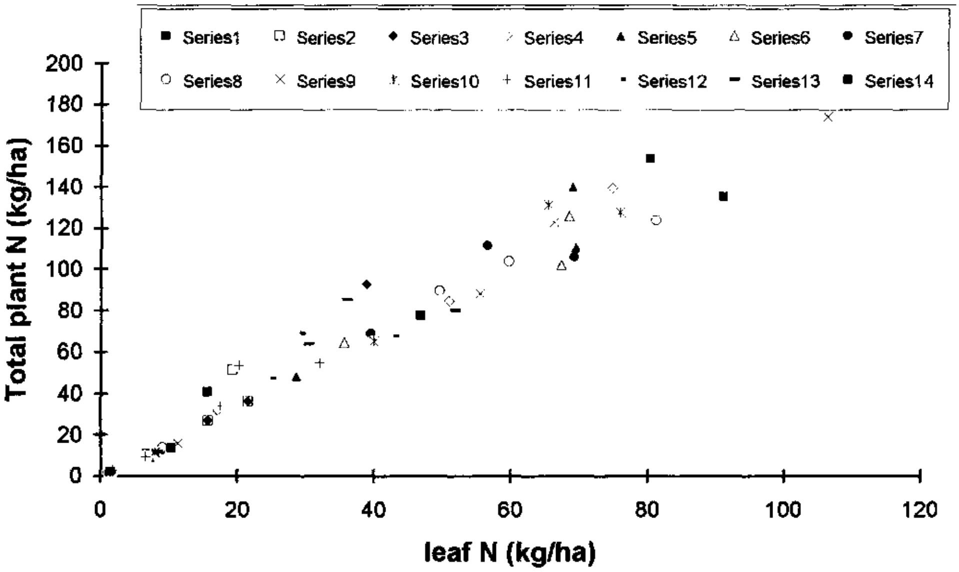

Figure 5. Total N as a function of leaf N (data up to flowering only) for all treatments in the field experiment.

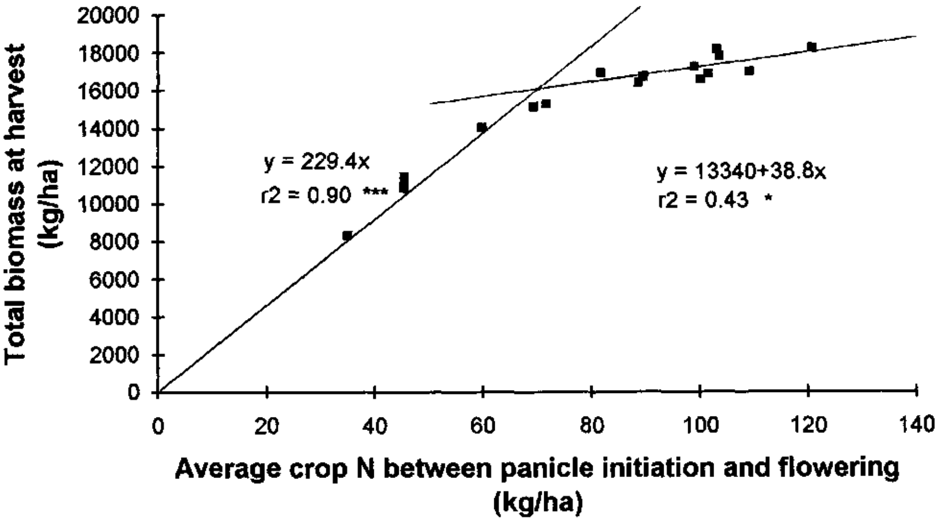

Figure 6. Total biomass as a function of average crop N content between panicle initiation and flowering for all treatments in the field experiment.

Total biomass and grain weight (corrected to 3% moisture) were strongly correlated with the average crop N status in this period (Figures 6 and 7). Total biomass and grain weight increased rapidly for crop N contents below 80 kg ha^{-1}. Larger crop N contents between panicle initiation and flowering did not result in an increase in grain weight, and only a slight increase in total biomass. N application before flowering showed to be very effective in increasing yield, but no yield increase was obtained if the amount of N applied before flowering exceeded 150 kg ha^{-1} (Figure 8). The number of spikelets per m^2 was strongly related to the increase in total crop dry weight between panicle initiation and flowering (Figure 9). The number of unfilled spikelets was greater at higher total numbers of spikelets per m^2 (Figure 9) and higher N application levels (Table 6). This may be due to 'source' limitations (i.e. not enough solar radiation during the grainfilling stage) or spikelet sterility problems.

Table 5. Average grain yields, harvest indices and N recovery percentages in the field experiment. Treatment codes are explained in Table 1. Grain yields are based on dry weights of grains without rachis, corrected to 14% moisture content. The harvest index is based on grain yields without rachis, corrected to 3% moisture content.

Treatment	Average grain yield	St. error grain yield	Harvest index	N recovery
	(t ha^{-1})	(t ha^{-1})	(-)	(%)
T0	4.8	0.5	0.52	-
T1+	5.1	0.5	0.41	33
T1-	4.9	0.3	0.40	52
T2+	8.3	0.1	0.49	56
T2-	8.6	0.3	0.51	63
T3+	9.7	0.3	0.52	48
T3-	9.6	0.1	0.53	53
T4	9.9	0.3	0.54	44
T5	9.7	0.4	0.52	51
T6	9.8	0.4	0.51	50
T7	8.8	0.5	0.44	27
T8	9.3	0.3	0.49	36
T9	10.1	0.1	0.50	46
T10	6.1	0.5	0.48	64
T11	6.9	0.3	0.45	63
T12	8.4	0.3	0.45	58
T13	9.7	0.3	0.48	44

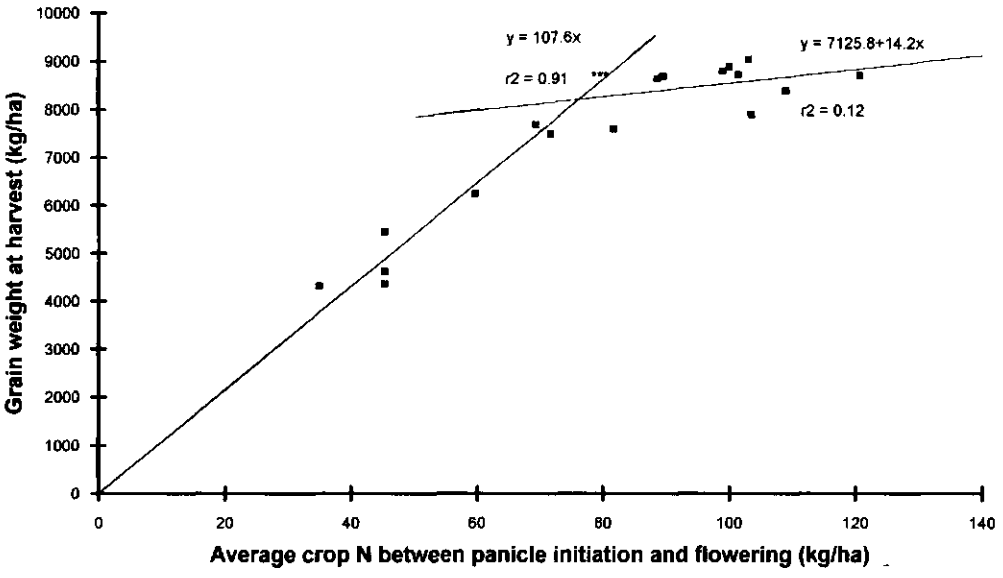

Figure 7. Final grain yield as a function of average crop N content between panicle initiation and flowering for all treatments in the field experiment.

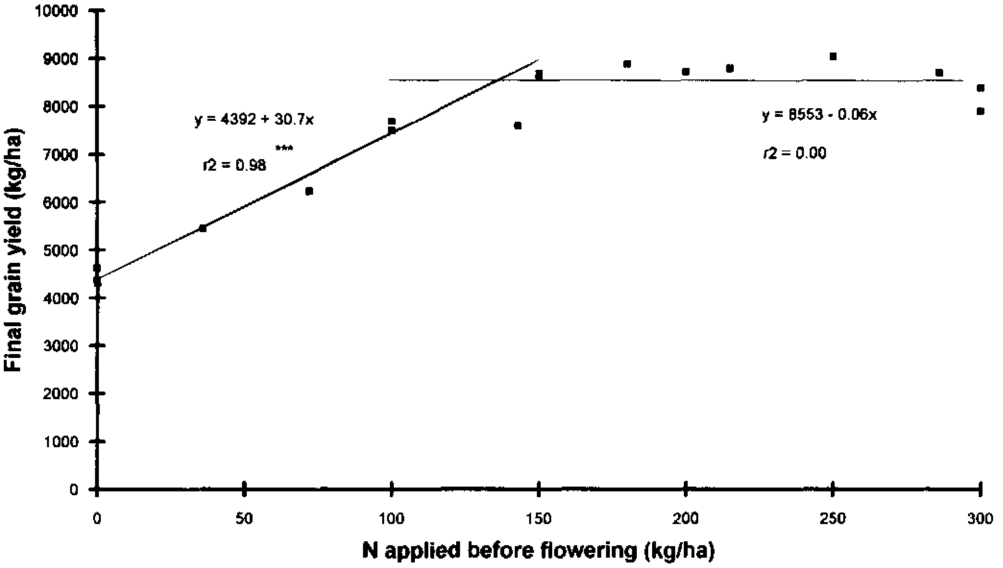

Figure 8. Final grain yield as a function of N applied before flowering for all treatments in the field experiment.

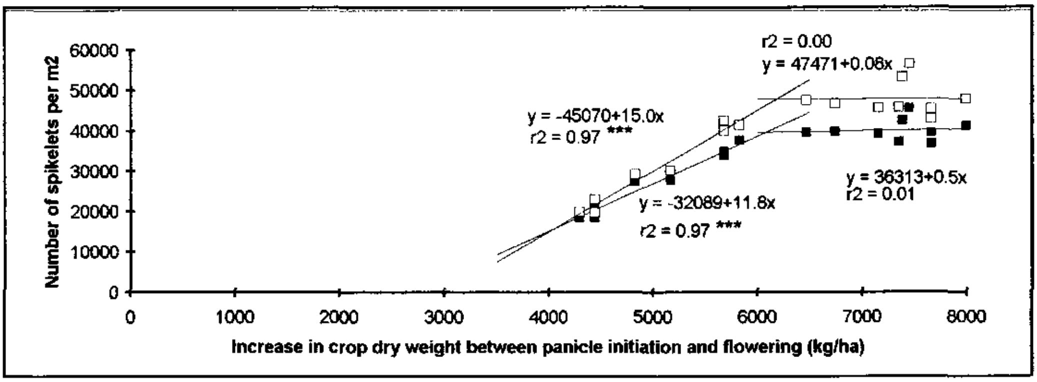

Figure 9. Total number of spikelets and filled spikelet number per m^2 as a function of increase in crop dry weight between panicle initiation and flowering for all treatments in the field experiment.

Table 6. Yield component analysis based on 6 hills sampled at harvest for each treatment in the field experiment. For comparison, calculated final yield (based on yield components) and 5.2 m^2 harvest area yield (corrected to 14% moisture content) are also shown. Treatment codes are explained in Table 1.

Treatment	1000 grain weight	nr. spikelets p. panicle	% filled spiks. p. panicle	nr. panicles per hill	calculated yield	harvest area yield
	(g)	(-)	(%)	(-)	(t/ha)	(t/ha)
T0	25.3	62	0.93	13	4.7	4.8
T1+	24.4	50	0.94	19	5.3	5.1
T1-	24.7	43	0.94	18	4.6	4.9
T2+	23.6	60	0.82	28	8.2	8.3
T2-	23.3	63	0.85	25	7.9	8.6
T3+	24.1	64	0.86	27	8.9	9.7
T3-	23.9	72	0.87	25	9.5	9.6
T4	24.2	80	0.86	24	10.0	9.9
T5	24.4	75	0.85	25	9.8	9.7
T6	25.0	74	0.83	26	9.9	9.8
T7	24.6	76	0.86	24	9.7	8.8
T8	24.2	79	0.81	23	9.0	9.3
T9	24.3	84	0.81	27	11.1	10.1
T10	25.2	75	0.94	16	6.9	6.1
T11	25.2	75	0.92	16	7.0	6.9
T12	25.0	70	0.91	24	9.4	8.4
T13	23.7	85	0.80	25	10.1	9.7

Conclusions

Postponing N application up until panicle initiation did not affect grain yield in the field experiment reported here. Yield differences among treatments were mainly due to differences in number of panicles per m^2 and number of spikelets per panicle, and were largely determined by crop N status in the period between panicle initiation and flowering. Larger sink sizes resulted in longer grain filling periods and therefore in a slower development rate in the reproductive phase. The percentage of unfilled grains per panicle increased at higher N application levels possibly due to spikelet sterility problems. Translocation of carbohydrates from stem and leaves to the grains was relatively unimportant. The optimum fertilizer application rate before flowering was 150 kg N ha^{-1}.

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Influence of substitution of fertilizer nitrogen by green manure on growth and yield of lowland rice

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Abstract

A field experiment was conducted at the Tamil Nadu Rice Research Institute, Aduthurai, India during the wet season of 1992 to study the use of green manure as an alternative nitrogen (N) source to chemical fertilizer for irrigated lowland rice. The experiment consisted of eight treatments, using urea (in 5 equal splits) and/or green manure as N source for the rice crop. Highest N uptake at lower N levels (100 kg/ha) was found if all nitrogen was applied in urea form. Highest N uptake at higher N levels (200 and 218 kg/ha) was observed if nitrogen was applied as green manure only or in combination with urea. Highest rice grain yield was recorded if 100 kg N/ha was applied as urea and 100 kg N/ha as green manure. Using green manure only resulted in the lowest agronomic efficiency.

Introduction

For most Asians, rice is the staple food, providing employment to a large sector of the rural population. Food production in India has increased three times over the last 20 years. This has been achieved through adoption of high yielding varieties, intensive cropping and improved management practices, including more intensive use of fertilizer. Nitrogen uptake by the rice plant is essential for even modest yields. However, energy shortages have increased nitrogen fertilizer costs, and future predictions suggest even higher prices (Brady, 1979). The cost of nitrogen (US dollar per 1000 kg of nitrogen) during the past decades in India increased from $51 (1950s), to $53 (1960s), $94 (1970s), $150 (1980s) (IRRI, 1990) and $194 (1990s). There was, therefore, a fourfold increase in the cost of fertilizer nitrogen from the 1950s to present. Recently, subsidies on fertilizer prices have been withdrawn in India and rice farmers with small land holdings are, therefore, more and more burdened with the high cost of chemical fertilizer. Hence, locally available alternative nitrogen sources need to be explored for use in lowland rice. In this context, green manures may offer a good and cheap alternative to inorganic fertilizer N.

A field experiment was conducted to study the use of green manure as a N source for growth and yield of lowland rice.

Materials and methods

The field experiment was conducted at the Tamil Nadu Rice Research Institute, Aduthurai, India (11°N, 77°E, 19m altitude) during the wet season (August - December) of 1992. The soil was classified according to Soil Taxonomy (Soil Survey Staff, 1975) as a fine Chromustert of clay loam texture. The experiment consisted of 8 fertilizer N/green manure treatments (Table 1) and was conducted in a randomized block design with four replications, using plots of 10 m × 3 m which remained flooded throughout the experiment.

Table 1. N fertilizer treatments in the field experiment (Aduthurai, wet season 1992).

Treatment	Sesbania N (kg/ha)	urea N (kg/ha)	Total N (kg/ha)
T1	-	100	100
T2	50	50	100
T3	100	-	100
T4	-	200	200
T5	100	100	200
T6	-	200	200
T7*	68**	150	218
T8	0	0	0

* Recommended practice

** 6.25 t/ha of green leaf manure

The chemical fertilizer was urea (46% N); the green leaf manure Sesbania rostrata. All treatments received 60 kg P/ha as super phosphate and 60 kg K/ha as muriate of potash. The full dose of P was applied basally at the time of transplanting. K was applied in three equal splits at basal, active tillering and panicle initation stages. Sesbania rostrata was broadcast at a seed rate of 125 kg/ha separately in another field and 50 day old plants were harvested for incorporation. The green leaf manure herbage was sampled from one m^2 area randomly in different places; composite samples were dried for 2 days at 80°C and nitrogen concentrations were determined using the micro-Kjeldahl method. The N content of Sesbania rostrata was 4.38%. The green leaf manure nitrogen application was computed on the basis of moisture and N content. The fresh biomass was chaffed, evenly spread on the main field and incorporated basally, a day before the rice was transplanted. Urea was applied in five equal splits, i.e. at the time of transplanting, active tillering, maximum tillering, panicle initation, and flowering stages. The test variety was ADT 38, a medium duration cultivar (135d). Seedlings (34 days old) were transplanted on 16 September 1993 (calendar day 260) in puddled soil, using one seedling per hill and a plant spacing of 20 cm × 10 cm (50 hills/m^2). Periodical plant samples were drawn and dried at 80^{o}C for 2 days to estimate the biomass of plant organs i.e., leaf, stem, root and panicles and also for N determination. Adequate crop protection measures were taken throughout the experiment.

Results and discussion

For all treatments flowering (defined as the moment when 100% of the hills have at least one flowering panicle) occurred around 77 DAT. All plots were harvested at 105 DAT.

Dry weight of plant organs
Dry weights of leaves (green and dead leaves), stems, roots and storage organs are presented in Table 2. For all treatments, stem weight decreased after flowering, indicating translocation of carbohydrates to the panicle.

Table 2. Dry weight (kg/ha) of leaves, stems, roots and storage organs (kg/ha) of cv ADT38 in the field experiment (Aduthurai, wet season 1992) at different days after transplanting (DAT). Treatment codes are explained in Table 1.

Treatment	DAT	Leaves	Stems	Roots	Storage organs	L+S+R+S
T1	0	16.0	11.5	7.0	-	34.5
	7	24.8	21.1	16.0	-	61.9
	14	83.7	76.9	54.5	-	215.1
	21	269.8	233.4	194.7	-	697.9
	28	531.1	533.0	293.7	-	1357.8
	37	1180.9	1083.6	609.8	-	2874.3
	44	1920.8	2254.3	999.0	-	5174.1
	59	2692.3	4375.8	1162.2	757.3	8987.6
	68	2713.2	4965.2	1656.7	1598.9	10934.0
	77	3064.8	5554.6	1563.9	4129.8	14313.1
	85	2399.7	4485.9	1214.0	5514.6	13614.2
	92	2100.7	4680.1	1078.5	6479.2	14338.5

Table 2 continued next page

Table 2 continued

Treat-ment	DAT	Leaves	Stems	Roots	Storage organs	L+S+R+S
T2	0	16.0	11.5	7.0	34.5	
	7	32.7	28.7	20.4	-	81.8
	14	95.3	80.2	53.1	-	228.6
	21	255.3	259.5	182.7	-	697.5
	28	495.6	477.7	262.5	-	1235.8
	37	1033.2	1062.6	562.1	-	2657.9
	44	1596.4	1963.9	795.1	-	4355.4
	59	2704.3	3504.6	1107.8	414.3	7731.0
	68	2568.5	4390.6	1575.8	1495.3	10030.2
	77	2501.1	5276.5	1312.3	3732.3	12822.2
	85	2244.4	4296.1	1133.0	4658.0	12331.5
	92	1879.0	4323.1	978.2	4790.8	11971.1
T3	0	16.0	11.5	7.0	-	34.5
	7	22.9	21.2	14.3	-	58.4
	14	79.5	67.8	39.8	-	187.1
	21	235.5	211.0	156.9	-	603.4
	28	434.2	454.4	252.2	-	1140.8
	37	1014.2	1004.2	546.3	-	2564.7
	44	1703.5	2095.5	789.9	-	4588.9
	59	2490.9	3981.6	1171.7	303.5	7947.7
	68	2539.9	4559.8	1555.4	1333.6	9988.7
	77	2735.9	5137.9	1375.8	3494.3	12743.9
	85	2319.4	4064.0	1105.6	5377.8	12866.8
	92	2006.6	4582.9	1017.7	5896.8	13504.0
T4	0	16.0	11.5	7.0	-	34.5
	7	27.0	25.5	14.5	-	67.0
	14	109.5	94.8	62.5	-	266.8
	21	330.9	302.3	205.9	-	839.1
	28	653.7	630.2	351.1	-	1635.0
	37	1211.3	1165.9	663.7	-	3040.9
	44	2316.1	2603.2	1049.9	-	5969.2
	59	3062.9	4209.0	1547.7	626.7	9446.3
	68	3276.6	4908.9	1700.8	1804.6	11690.9
	77	2826.2	5608.8	1566.9	4235.0	14236.9
	85	2609.4	5076.7	1463.8	6347.6	15497.5
	92	2330.2	5254.9	1199.6	7286.5	16071.2

Table 2 continued next page

Table 2 continued

Treat-ment	DAT	Leaves	Stems	Roots	Storage organs	L+S+R+S
T5	0	16.0	11.5	7.0	-	34.5
	7	29.7	24.5	19.7	-	73.9
	14	103.5	92.4	68.6	-	264.5
	21	310.5	294.2	189.8	-	794.5
	28	784.6	725.2	340.2	-	1850.0
	37	1237.8	1085.2	763.3	-	3086.3
	44	2031.3	2561.8	1182.9	-	5776.0
	59	3578.2	5125.6	1690.2	537.4	10931.4
	68	3089.9	5442.3	2029.8	1976.8	12538.8
	77	2970.3	5758.9	1673.6	4420.3	14823.1
	85	2724.3	4733.4	1482.2	6741.8	15681.7
	92	2580.2	4714.7	1293.4	7439.5	16027.8
T6	0	16.5	11.0	7.0	-	34.5
	7	28.5	23.1	13.9	-	65.5
	14	77.1	76.9	49.7	-	203.7
	21	266.9	249.0	178.7	-	694.6
	28	488.3	498.3	318.8	-	1305.4
	37	1039.6	1069.4	612.5	-	2721.5
	44	1918.7	2231.7	795.1	-	4945.5
	59	2453.5	3998.2	1047.7	177.7	7677.1
	68	2690.3	4722.2	1609.1	1790.8	10812.4
	77	2755.7	5446.2	1434.4	3978.2	13614.5
	85	2414.6	4592.5	1314.0	5663.7	13984.8
	92	2400.0	4503.8	1014.6	6344.9	14263.3
T7	0	16.0	11.5	7.0	-	34.5
	7	35.3	31.0	23.4	-	89.7
	14	97.4	85.1	61.2	-	243.7
	21	338.7	327.0	218.2	-	883.9
	28	551.7	530.6	308.2	-	1390.5
	37	1200.8	1168.4	728.6	-	3097.8
	44	2487.8	2500.6	1013.4	-	6001.8
	59	3381.1	4605.2	1261.1	691.6	9939.0
	68	3187.4	5463.9	1638.3	1966.0	12255.6
	77	3166.5	6322.5	1949.8	5532.3	16971.1
	85	2861.5	5150.2	1800.2	6267.6	16079.5
	92	2574.4	4995.3	1168.2	7371.9	16109.8

Table 2 continued next page

Table 2 continued

Treatment	DAT	Leaves	Stems	Roots	Storage organs	L+S+R+S
T8	0	16.0	11.5	7.0	-	34.5
	7	24.0	26.7	16.7	-	67.4
	14	61.0	52.4	42.0	-	155.4
	21	188.7	172.8	157.6	-	519.1
	28	470.3	429.8	238.2	-	1138.3
	37	928.5	990.9	496.8	-	2416.2
	44	1547.3	1871.2	694.8	-	4113.3
	59	2160.0	3510.0	847.1	961.1	7478.4
	68	2190.7	3937.1	1406.8	1063.4	8598.0
	77	1833.4	4363.9	989.9	2997.1	10184.3
	85	2160.6	4027.8	1010.7	4042.5	11241.6
	92	1781.4	3164.9	857.8	4217.7	10021.8

Nitrogen content of plant organs

Nitrogen contents of leaves, stems, roots and storage organs are presented in Table 3. N content for leaves and stems peaked during active tillering stage (14-21 DAT), and decreased continuously up to harvest afterwards. Application of urea caused temporary increases of tissue N content during the crop cycle. In general a rapid decline was observed between 21 and 44 DAT. Root N content decreased continuously up to harvest, showing a very steep decline between transplanting and 14 DAT.

Table 3. N content (%) of leaves, stems, roots and storage organs (kg/ha) of cv ADT38 in the field experiment (Aduthurai, wet season 1992) at different days after transplanting (DAT). Treatment codes are explained in Table 1.

Treatment	DAT	Leaves	Stems	Roots	Storage organs
T1	0	3.40	4.14	4.38	-
	7	4.32	4.45	3.85	-
	14	3.70	3.56	2.21	-
	21	4.01	3.12	1.77	-
	28	4.02	3.10	1.79	-
	37	3.25	2.38	1.38	-
	44	2.89	1.98	1.49	
	59	2.50	2.54	1.32	2.54
	68	2.19	1.80	1.24	1.41
	77	2.09	0.99	1.09	1.45
	85	1.49	0.94	1.15	1.46
	92	1.09	0.96	0.32	1.68

Table 3 continued next page

Table 3 continued

Treatment	DAT	Leaves	Stems	Roots	Storage organs
T2	0	3.40	4.14	4.38	-
	7	4.02	4.45	3.49	
	14	3.79	3.56	2.10	-
	21	4.18	2.89	1.72	-
	28	3.92	2.98	1.77	-
	37	3.41	2.28	1.45	-
	44	2.69	2.67	1.44	-
	59	2.09	1.77	1.14	1.77
	68	2.27	1.28	1.30	1.07
	77	2.15	0.79	1.04	1.12
	85	1.44	0.87	1.04	1.21
	92	1.08	0.76	0.43	1.65
T3	0	3.40	4.14	4.38	-
	7	4.04	4.05	2.33	
	14	3.04	3.23	2.05	-
	21	4.12	2.67	1.91	-
	28	3.91	2.84	1.78	-
	37	3.90	2.25	1.46	-
	44	2.36	2.27	1.37	-
	59	2.01	1.21	1.20	1.21
	68	2.10	1.05	0.74	1.35
	77	1.87	0.88	1.09	1.46
	85	1.44	0.78	1.08	1.60
	92	1.10	0.71	0.38	1.65
T4	0	3.40	4.14	4.38	-
	7	4.48	5.66	3.18	-
	14	5.08	3.62	2.05	-
	21	5.07	3.38	2.24	-
	28	4.52	3.18	2.04	-
	37	3.56	2.36	1.58	-
	44	2.54	2.50	1.39	-
	59	2.34	2.20	1.35	2.20
	68	2.19	1.64	1.09	1.32
	77	2.15	1.08	1.19	1.46
	85	1.46	1.09	1.29	1.60
	92	1.21	0.82	0.82	1.88

Table 3 continued next page

Table 3 continued

Treatment	DAT	Leaves	Stems	Roots	Storage organs
T5	0	3.40	4.14	4.38	-
	7	4.82	4.12	2.50	-
	14	3.84	3.56	2.32	-
	21	4.29	3.28	2.01	-
	28	4.24	3.61	1.88	-
	37	3.46	2.44	1.57	-
	44	2.60	2.89	1.66	-
	59	2.32	2.09	1.20	2.09
	68	2.12	1.65	1.22	1.66
	77	2.16	1.20	1.09	1.71
	85	1.61	1.15	1.05	1.78
	92	1.15	0.83	0.99	1.71
T6	0	3.40	4.14	4.38	-
	7	3.72	4.12	3.61	-
	14	3.67	3.06	1.87	-
	21	4.24	3.06	1.77	-
	28	4.24	3.00	1.82	-
	37	2.93	2.27	1.35	-
	44	2.15	2.50	1.24	-
	59	2.20	1.90	1.15	1.90
	68	1.94	1.50	1.12	1.60
	77	1.96	1.09	1.02	1.60
	85	1.39	1.26	0.97	1.78
	92	1.20	0.75	0.89	1.68
T7	0	3.40	4.14	4.38	-
	7	4.68	4.48	3.66	-
	14	3.84	3.84	2.00	-
	21	4.93	3.14	2.05	-
	28	4.50	3.33	1.89	-
	37	3.40	2.70	1.88	-
	44	2.41	2.39	1.38	-
	59	2.25	2.66	1.15	2.66
	68	2.29	1.98	1.15	1.83
	77	2.34	1.30	1.20	1.86
	85	1.45	1.09	1.15	1.77
	92	1.09	0.76	1.02	1.82

Table 3 continued next page

Table 3 continued

Treatment	DAT	Leaves	Stems	Roots	Storage organs
T8	0	3.40	4.14	4.38	-
	7	3.79	4.19	2.56	-
	14	2.94	3.38	2.08	-
	21	3.62	2.72	1.66	-
	28	3.01	2.95	1.39	-
	37	2.90	2.66	1.29	-
	44	2.10	1.85	0.88	-
	59	1.72	1.71	0.99	1.71
	68	1.98	1.35	0.94	1.27
	77	1.78	0.98	0.88	1.78
	85	1.04	0.96	1.01	1.77
	92	1.05	0.71	0.59	1.55

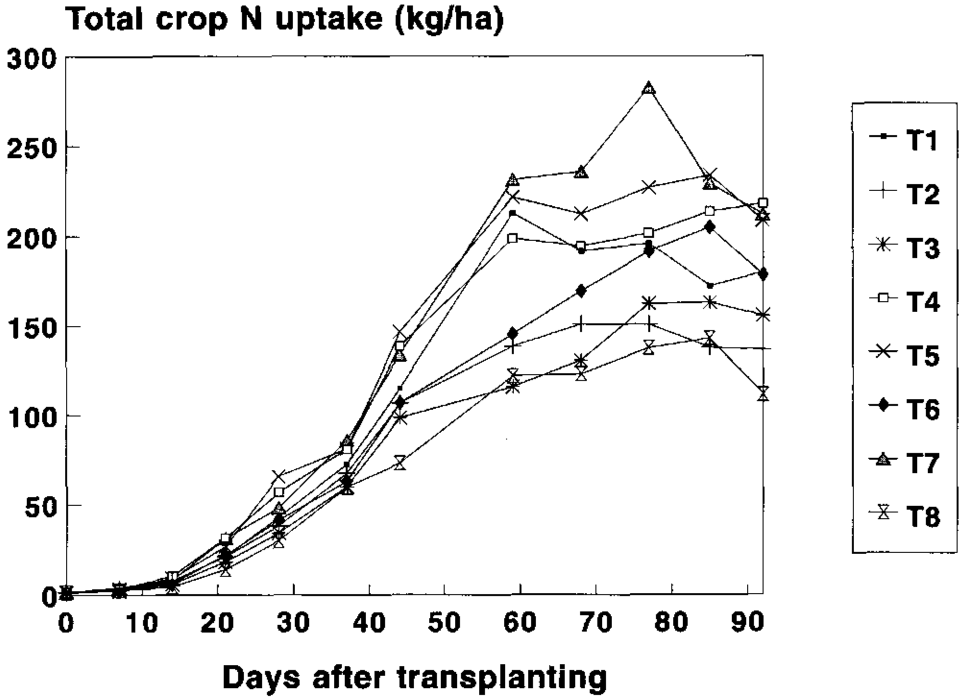

Figure 1. Total N uptake at different days after transplanting for ADT38 in the field experiment (Aduthurai, India, wet season 1992). Treatment codes are explained in Table 1.

Total nitrogen uptake

Among all treatments, the total nitrogen uptake (Figure 1) was maximum (283 kg/ha) in T7, followed by T5 (234 kg/ha) and T4 (218 kg/ha). The uptake was lower in T8 (143 kg/ha), T3 (163 kg/ha) and T2 (151 kg/ha). The maximum uptake was recorded at 59 DAT in T1, 77 DAT in T7, 85 DAT in T3, T6, T8 and 68 DAT in T2, 92 DAT in T4 and 85 DAT in T5. In general, total nitrogen uptake increased linearly with total amount of nitrogen applied (0 to 218 kg N/ha). Both at lower (100 kg N/ha) and higher (200 kg N/ha) N application levels, the N uptake was lowest if Sesbania was used as the only N source (T3 and T6). Similar results were obtained by Dascalsota (1986).

Agronomic efficiency (AE)

The agronomic efficiency of each treatment, i.e., the increase in grain yield per unit of nitrogen input was computed as follows :

$$\mathrm{AE} = \frac{\text{Grain yield in fertilized plot (kg / ha) - Grain yield in unfertilized plot (kg / ha)}}{\text{Quantity of fertilizer N applied (kg / ha)}}$$

The highest agronomic efficiency was recorded if 100 kg N/ha was applied as urea (Table 1) The next best efficiency was observed if 100 or 200 kg N/ha was applied as a combination of urea and sesbania. Higher nitrogen application levels decreased the agronomic efficiency.

Conclusions

1. At 100 kg N application level, the highest uptake of nitrogen was recorded when the N source was inorganic whereas at 200 and 218 kg N/ha, the highest uptake was seen when the N source was inorganic as well as integrated source.
2. 200 kg N/ha applied in two equal proportions as organic (green leaf manure) and inorganic (fertilizer) source gave the highest rice grain yield and N uptake.
3. At lower nitrogen level (100 kg N/ha),the inorganic source was better than organic or the integrated source.
4. The agronomic efficiency was significantly higher in inorganic and integrated source than organic source.
5. Nitrogen translocation from stem to grains was influenced by the sources of N but there was less significant influence on the N translocation from leaves by the N sources.

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Nitrogen uptake of rice as influenced by green manure, grain legumes and fertilizer N

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Introduction

Nitrogen is considered to be the key to realizing the yield potentials of high yielding varieties. Considering the very low efficiency of applied N fertilizers and the possibility of only a partial substitution to the rice crop in a system, it has become imperative to integrate the use of organic and inorganic sources of N for higher N use efficiency, increased yield and sustained fertility. Integrated use of green manures, including pulses and incorporating their haulms after harvesting pods, inorganic N fertilizer and crop residue management have received attention in recent years for efficient and economic management of N in rice-based cropping systems (Meelu and Morris, 1987). Unlike the inorganic fertilizers, the ammoniacal N released by green manures during decomposition has a linear relationship with N uptake and yield of the rice crop (Schon et al., 1985). Residues of grain legumes, which frequently have a lower N content than that of green manures, also rapidly release ammonium in tropical flooded soils. Nagarajah (1988) found that the net recovery of plant N as ammonium, from five grain legumes at 50 days of incubation in flooded soils, ranged from 16 to 20% and it correlated directly with plant N and inversely with C-N ratio. With a view to study the effect of different organic and inorganic N sources on the N uptake pattern of rice in an intensive cropping system of rice-rice-grain legume this study was taken up.

Materials and methods

A field experiment was conducted from 1988 to 1990 at Tamil Nadu Agricultural University, Coimbatore, India to study the N uptake pattern of rice crops in the rice-rice-greengram cropping system with the inclusion of green manure, grain legumes and application of fertilizer N. The soil of the experimental field was a moderately drained deep clay loam (Typic Haplustalf), medium in available N and P and high in available K. The organic carbon content was 0.69 per cent.

The treatments included 6 cropping systems: rice-rice greengram (S_1), green manure (Sesbania rostrata) -rice-rice-greengram (S_2), rice-green manure-rice-greengram (S_3), blackgram-rice-rice-greengram (S_4), soybean-rice-rice-greengram (S_5) and cowpea-rice-rice-greengram (S_6), and 3 nitrogen levels (0, 50 and 100 kg N ha-1). The cropping systems ware allotted to main plots and the N levels to the sub-plots in a split plot design, replicated thrice. The gross and net plot size for each treatment was 40.8 m^2 (8.0 × 5.1 m) and 26.5 m^2, respectively. The fertilizer N was applied to both the first an second season rice crops only (50% basal, 25% at active tillering, and 25% at PI) according to the treatment schedule. The green manures/grain legumes were raised without any fertilization. The entire quantity of green manure obtained and the haulms of the grain legumes, after harvesting their pods for grain, were turned into the soil as a source of organic N. Aboveground plant samples of rice were collected at active tillering, panicle initiation, flowering and maturity stages, and biomass and N contents were determined. The direct effect of the green manures was studied both during the first rice (South west monsoon season - SWM) and second rice (North east monsoon season - NEM) in the green manure-rice-rice-greengram and rice-green manure-rice-greengram systems, respectively. Rice varieties were IR50 during SWM (July - Oct.) and IR60 during NEM (Oct. - Jan.). Grain legumes in systems S_4 to S_6 were grown between May and July.

The residual effect of green manure and grain legumes applied to the SWM rice crop was assessed on the subsequent NEM rice. Pre-experimental and post-harvest soil samples were collected from a depth of 0 - 20 cm after each crop for the estimation of available N (alkaline permangate method) and the N balance was worked out to find out the extent of contribution of sources in sustaining soil fertility levels. Two annual cropping cycles of the systems were completed during the study without disturbing the experimental field lay-out.

Results and discussion

The biomass produced by the green manure, haulm yield of different grain legumes and N added to the soil by these organic sources are presented in Table 1. The green manure, S. rostrata, raised during the pre-SWM rice crop, produced higher quantity of biomass than that raised in the pre-NEM season. S. rostrata is a short day plant (Visperas et al., 1987). The day length was more during summer which preceded the SWM rice and this extended the vegetative phase, resulting in higher biomass production. The short day length in pre-NEM season (October - December) induced early flowering, restricted the growth and resulted in lower biomass. Among the grain legumes, cowpea produced the largest amount of haulms. The amount of N accumulated by the pre-SWM green manure was the highest followed by that grown during pre-NEM. The amount of N added via the haulms of different grain legumes varied from 34 to 52 kg ha during 1988 and 1989 and the highest was with cowpea.

Table 1. Quantity of biomass added and N contributed by different organic sources.

Source	Fresh biomass ($t\ ha^{-1}$)				N added ($kg\ ha^{-1}$)			
	Pre-SWM		Pre-NEM		Pre-SWM		Pre-NEM	
	1988	1989	1988	1989	1988	1989	1988	1989
Green manure (Sesbiana rostrata)	23.9	21.2	9.6	10.8	160	143	84	96
Blackgram (Phaseolus mungo)	1.9	1.8	-	-	40	43	-	-
Soybean (Glycine max)	2.0	2.4	-	-	34	41	-	-
Cowpea (Vigna unguiculata)	2.6	3.0	-	-	49	52	-	-

Nitrogen uptake by rice as influenced by green manuring, grain legume haulms incorporation and fertilizer N application during SWM and NEM seasons are depicted in Figures 1 and 2. The organic N sources incorporated before transplanting lowland rice crop undergo decomposition, releasing NH_4^+-N into the soil solution which is readily used by the rice plants. N uptake by the rice was greater when green manure was incorporated than with grain legume haulms. Among the grain legumes, cowpea haulms incorporation enhanced the N uptake by rice compared to blackgram and soybean. S. rostrata raised as green manure accumulated greater quantities of N, because of its higher biomass production. Besides, its biomass is easily decomposable due to its narrow C-N ratio, (about 15:1) and lower lignin content (9.4%) (Nagarajah et al., 1989). S. rostrata was incorporated at 50 days after sowing (DAS) when it was in the peak vegetative phase during the SWM season and in the flowering phase in the NEM season. On the other hand, the grain legume haulms were incorporated after harvesting their pods around 75 DAS. As the plant matures, the C-N ratio and lignin content increase and the plant N content decreases (John et al., 1989). The net recovery of plant N is correlated directly to the plant N content and inversely with C-N ratio and lignin content (Buresh and De Datta, 1991). The rate of mineralisation of soybean haulms and release of NH_4^+-N has been reported to the lower because of its lower plant N content and wide C-N ratio. The net release of plant N at 50 days after incubation was only 16% for soybean compared to 28% for cowpea and 43% for S. rostrata (Nagarajah, 1988).

Nitrogen accumulation in rice was slower between active tillering and panicle initiation stages and it increased considerably from panicle initiation to flowering. Thereafter the rate of N uptake slowed down. Since in case of organic source all N was applied before transplanting, and the inorganic N was applied during the early stages (50% as basal, 25% at active tillering and 25% at panicle initiation), the rate of N uptake was higher in the early stages. The N mineralised during the decomposition of green manure and grain legume haulms is supposed to enhance the N availability in the rhizosphere resulting in increased N uptake by rice, which, in turn, promotes vegetative growth.

Application of varied doses of fertilizer N influenced the N uptake. The magnitude of increase was higher between 0 and 50 kg N ha^{-1} level. The influence of varied treatments and treatment combinations on the uptake of N was similar at all the four stages of observation, though the magnitude was varying.

The direct and residual effect of the N uptake by rice plant are ultimately measured in terms of grain productivity. Green manuring increased the rice yield to a considerable extent (Table 2). Mineralisation of green manure ensures a continuous supply of $NH_4^+ - N$ which is preferred and readily absorbed by rice plants resulting in better growth. This improved the yield attributes such as number of productive tillers and the number of filled grains in the panicle. Higher yields with addition of cowpea and blackgram haulms, compared to soybean haulms, is also attributed to the increased availability of N from mineralisation of cowpea and blackgram haulms. Though the response was significant for the application of fertilizer N up to 100 kg ha^{-1}, the response tended to decrease after 50 kg ha^{-1}. Declining rate of response of rice to increasing levels of added N was well documented (Savant and De Datta, 1982).

The residual effect of green manuring and grain legume haulms incorporation to lowland rice is generally measured in terms of grain yield of the succeeding crop. The residual effect of green manuring the SWM rice on the subsequent NEM rice grain yield was only 7.1 and 6.6% during 1988 and 1989, respectively, as compared to S_1 yields.

Table 2. Effect on organic and inorganic N sources on the grain yield of rice (t ha^{-1}).

System		SWM rice		NEM rice	
		1988	1989	1988	1989
R - R - GG	(S_1)	4.35	4.28	3.97	3.70
GM - R - R - GG	(S_2)	5.43	5.14	4.25	3.94
R - GM - R - GG	(S_3)	4.35	4.06	4.67	4.47
BG - R - R - GG	(S_4)	4.70	4.38	4.11	3.85
SB - R - R - GG	(S_5)	4.60	4.20	4.03	3.78
CP - R - R - GG	(S_6)	4.80	4.45	4.15	3.90
LSD (5%)		0.26	0.31	0.32	0.33
0 kg N ha^{-1}	(N_0)	3.72	3.39	3.26	3.01
50 kg N ha^{-1}	(N_{50})	4.88	4.54	4.30	3.98
100 kg N ha^{-1}	(N_{100})	5.50	5.34	5.04	4.83
LSD (5%)		0.30	0.27	0.15	0.18

R	: Rice	GG	: Greengram	BG	: Blackgram
SB	: Soybean	CP	: Cowpea	GM	: Green Manure

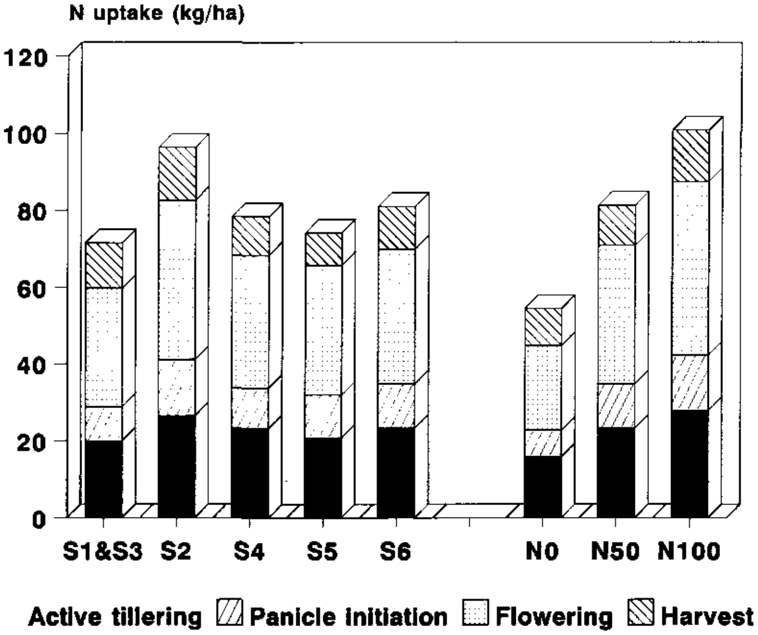

Figure 1a. Nitrogen uptake of rice at different growth stages, Coimbatore, SWM season 1988.

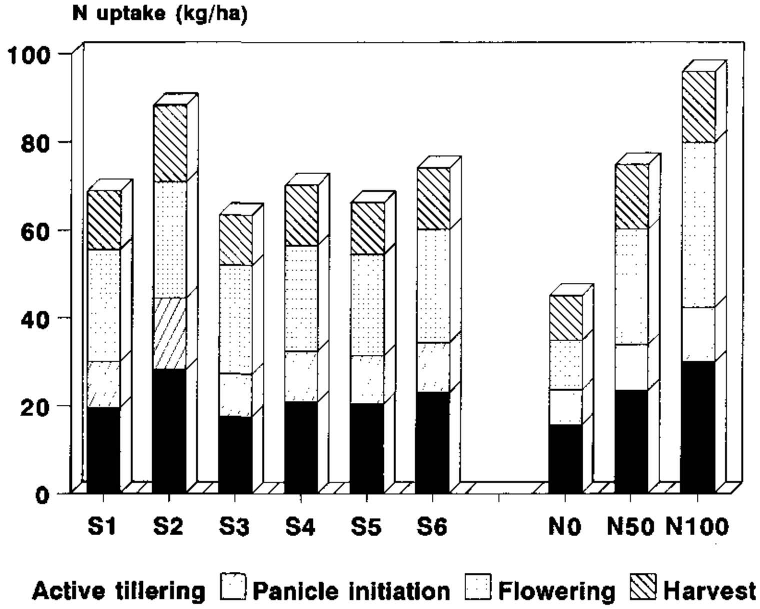

Figure 1b. Nitrogen uptake of rice at different growth stages, Coimbatore, SWM season 1989.

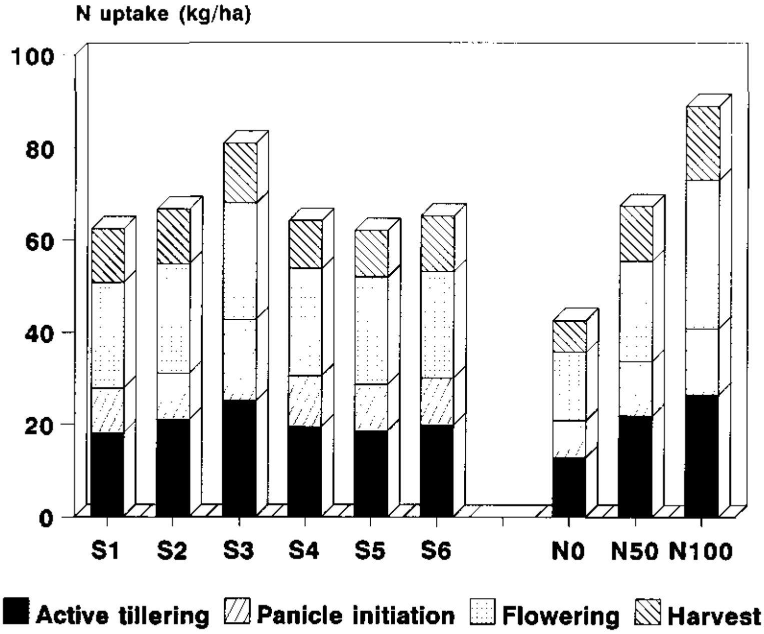

Figure 2a. Nitrogen uptake of rice at different growth stages, Coimbatore, NEM season 1989.

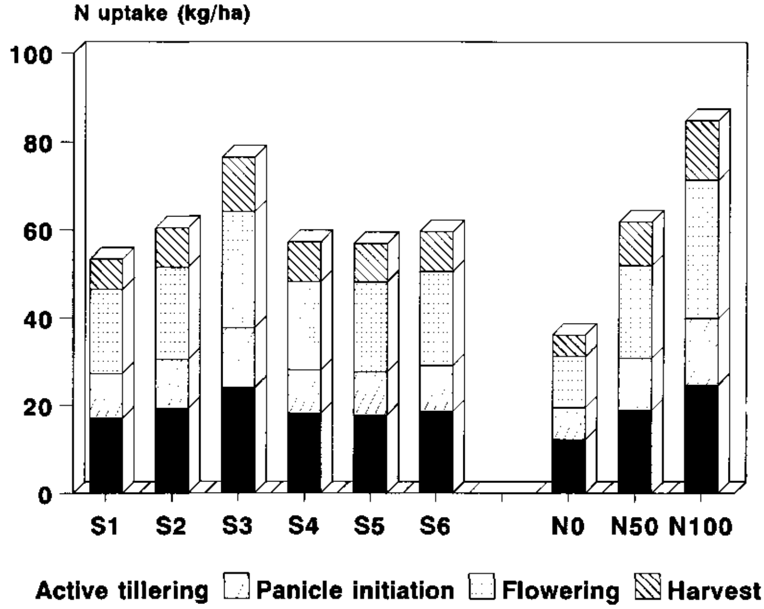

Figure 2b. Nitrogen uptake of rice at different growth stages, Coimbatore, NEM season 1989.

Incorporation of grain legume haulms did not show any appreciable residual effect, the increase in grain yield being 1.4 to 5.3% only. Under tropical conditions, the residual effects are likely to be smaller than under temperature climate. The residual effect of green manure on the second crop of rice are related to the quantity of biomass added and the number of applications made per year. Only the cumulative effect of several annual applications are expected to bring an appreciable residual effect (Bouldin, 1988).

The effect of different organic sources and inorganic fertilizer N application on soil available N was studied through N balance (Table 3). The net N balance of the soil can be calculated by subtracting the initial from the final (after 2 years) soil available N content (by permanganate method). This shows that green manuring and incorporation of grain legume haulms increased available soil N. Alternatively, the net N input I_{net} (kg N/ha) into the whole production system can be evaluated as

$$I_{net} = \text{final soil N - initial soil N - added fertilizer N + amount removed by crops}$$

This variable is included in Table 3. It reflects the net intake of N from sources other than fertilizer N: fixation of N_2, inputs from the atmosphere (precipitation), and possibly disclosure of soil N pools previously inaccessible by the permanganate method used. I_{net} was highest (upto 254 kg N/ha) in the systems incorporating green manure, followed by grain legume; and was lowest (down to 45 kg N/ha) where both these components were absent. Within each of these groups, I_{net} was inversely related to the level of additional urea input. It has also been hypothesised that legumes grown in rotation with lowland rice can intercept soil mineral N, which might, otherwise, be lost by denitrification or leaching after flooding the soil, and this helps recycling soil N for uptake by rice (Singh, 1984).

Table 3. Components of the N balance (kg N ha^{-1}) of rice-based cropping systems, (GM/GL-Rice-Rice-Greengram) as evaluated over two years.

System	N added			N removed by crops**	Computed balance*	Final soil N	Soil Net gain	I_{net} (kg N/ha)
	Applied	Residue	Total					
Control	-	17	17	255	55	214	-79	176
50 kg N	200	26	226	360	251	268	-25	135
100 kg N	400	36	436	443	286	295	+2	45
GM alone	-	344	344	310	327	237	-56	254
GM + 50 kg N	200	353	553	425	420	296	+3	228
GM + 100 kg N	400	380	580	502	370	326	+33	135
GL alone	-	119	119	309	109	226	-67	242
GL + 50 kg N	200	133	133	420	206	275	-18	202
GL + 100 kg N	400	138	538	491	341	301	+8	99

* Initial soil 293 kg N ha^{-1} ** Two annual cropping cycles of 8 crops
N applied to rice crops (4) only, GM: Green Manure, : GL: Grain Legume (cowpea)
A: applied; R: residue; T: total

Summary and conclusions

The nitrogen uptake of rice was influenced by the quantum of N supplied by different sources. Nitrogen uptake was the highest when green manure was directly incorporated to rice followed by cowpea and blackgram haulms addition. Increased levels of fertilizer N application enhanced the N uptake of rice. The magnitude of increase was higher between zero and 50 kg N/ha levels. The residual effect of green manuring and grain legume haulms addition was not appreciable on the subsequent crops. Crop N accumulation was slower between active tillering and panicle initiation to flowering stages. Thereafter the rate of N uptake slowed down. There was no substantial loss or gain in soil available N balance when green manuring was done and 50 kg N/ha was applied to each of the rice crops in the system. The balance was positive when 100 kg N was applied either alone or in combination with green manure and/or grain legume haulms incorporation. The net input of N into the system over two years, from sources other than fertilizer N was highest in the treatment receiving green manure only, and lowest in the treatment receiving 100 hg urea N at each cycle.

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Soil ammonium dynamics and nitrogen uptake by lowland rice on several soil types in West Java

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Abstract
Application of 90 kg/ha of urea-N to lowland rice during a rainy season field experiment conducted on five different soil types in West Java increased crop nitrogen (N) uptake, biomass production and grain yield. Ammonium concentration in soil solution and in the adsorbed phase decreased steadily after urea application. A base value was reached sooner for the solution than for the adsorbed phase. No good relation was found between ammonium concentration in solution and in adsorbed phase. Total N uptake and rice grain yields were higher at all sites when briquetted urea was applied in 2 splits than when applied in one dressing or in the form of prilled urea broadcast in three splits.

In a comparison among soil types, the integral of solution ammonium concentration over time was linearly related to total N uptake in unfertilized plots. Correlation was poor for fertilized plots. Recovery values under different N application methods varied from 0.05 to 0.87 kg N uptake per kg N applied. Mean (over application methods, per soil type) fertilizer N recovery was linearly and negatively related to the native soil fertility expressed as season total N uptake from unfertilized plots (r^2=0.88).

Introduction

The apparent recovery of fertilizer nitrogen (ANR) is defined as the nitrogen (N) uptake in excess of uptake in a control treatment receiving no fertilizer N, divided by the total amount of N applied. ANR in Indonesian lowland rice soils varies from 0.1 to 0.7 kg/kg (Sismiyati et al., 1990) depending on soil type, fertilizer application method and application level. In order to increase overall N use efficiency in rice production systems, the recovery of nitrogen from fertilizer should be increased. This requires proper fertilizer N management, by choosing for given soil, variety and weather conditions an optimal N application strategy, i.e. form, timing of splits, dose applied per split, and total dose. To achieve this, site specific N application rates and methods should be based on quantitative understanding of the behaviour of fertilizer N after entering the soil in relation to chemical and physical soil properties.

Recovery increases if the availability of ammonium in soil solution matches the pattern of N demand by the crop (Makarim et al., 1992; Ishizuka, 1976). In the study reported here we investigated the availability of ammonium in soil solution and in the adsorbed phase in five flooded rice soils in West Java under various N application methods.

Materials and methods

A field experiment was conducted during the rainy season (RS) of 1991 - 1992 in farmers fields at Pangelaran, Citayam, Cianjur, Rengasdengklok, and Lebak, all in West Java, Indonesia. Soil types were classified (FAO classification) as Regosol (Pangelaran), Ferralsol (Citayam), Vertisol (Cianjur), Fluvisol (Rengasdengklok) and Acrisol (Lebak). The physical and chemical characteristics of these soils determined prior to the experiment are listed in Table 1. All soils were slightly acidic to acid, and all except the Pagelaran soil had high clay contents. Clay at Citayam was of the kaolinite type.

Four N fertilizer treatments were imposed. Treatment T1 received no fertilizer nitrogen; T2 received 90 kg N/ha in the form of prilled urea in three equal splits at 7, 21 and 42 days after transplanting (DAT); T3 received 90 kg N/ha in the form of urea briquettes applied at 7 DAT as four granules of 1 g per four hills; T4 received 90 kg N/ha in the form of urea briquettes applied at 7 and 21 DAT as two granules of 1 g per four hills on both dates (Table 2).

The experiment layout was a randomized block design with three replications. Plot size was 4 m x 5 m. 21 d old seedlings of rice cvar IR64 were transplanted on December 4, 11, and 13, 1991, at Rengasdengklok, Cianjur and Citayam, respectively; and on January 3 and 13, 1992, at Lebak and Pagelaran. Plant spacing was 20 cm x 25 cm at all sites. A blanket application of 100 kg triple superphosphate and 100 kg KCl per ha was given at transplanting in all treatments.

Soil solution and solid phase were sampled at 8, 15, 22, 29, 43 and 50 DAT. Soil solution was collected by suction with the help of one 12 cm long microporous synthetic tube per plot, inserted vertically at 10-22 cm depth. Five soil samples per plot were collected from the puddled layer and mixed into a composite sample for extraction with 1 N KCl. Ammonium concentrations in the soil solution samples and in the soil extracts were determined by colorimetry (Nessler reagens) at 432 nm.

Grain yield and straw (leaves, stems, rachis) biomass were determined at harvest; N contents of straw and grains were determined. Yield components (number of panicles per hill, number of grains per panicle, 1000 grain weight, and percentage of spikelets unfilled) were also measured at this stage. The crop was harvested on March 2, 15, 26, and 31, 1992, at Rengasdengklok, Cianjur, Citayam and Lebak, respectively, and on April 11 at Pagelaran.

Table 1. Chemical and physical properties of five soils at different sites in West Java. Rainy season 1991-1992.

Properties	Pagelaran	Citayam	Cianjur	Rengasdengklok	Lebak
Texture:					
Sand (%)	35.6	2.0	7.5	1.3	28.9
Silt (%)	42.1	24.5	38.0	24.0	21.7
Clay (%)	22.3	73.5	54.5	74.7	49.4
pH H_2O (1:2.5)	5.8	6.3	5.7	5.4	5.7
KCl (1:2.5)	4.8	5.3	5.0	4.3	4.7
Organic C (%)	1.84	1.44	2.53	1.68	1.72
Total N (%)	0.20	0.16	0.30	0.11	0.15
C/N Ratio	9.1	9.00	8.5	16.0	11.4
Available P (mg/100 g)	8.7	0.41	0.20	0.42	0.50
Cation contents:					
Ca (me/100 g)	7.15	3.13	12.54	5.59	3.01
Mg (me/100 g)	2.45	1.59	2.88	1.98	1.70
K (me/100 g)	0.32	0.42	0.59	0.66	0.36
Na (me/100 g)	0.65	N.D.	0.66	0.41	0.49
CEC (me/100 g)	24.0	19.3	40.3	36.2	18.2
Cation no. (me/100 g)	10.6	5.1	16.7	8.2	5.07
Base saturation (%)	44.0	26.6	41.4	22.7	27.8
Micro elements:					
Fe (ppm)	109.1	1.5	76.0	124.4	8.3
Mn (ppm)	52.6	25.6	119.4	54.5	29.1

N.D. = Not determined

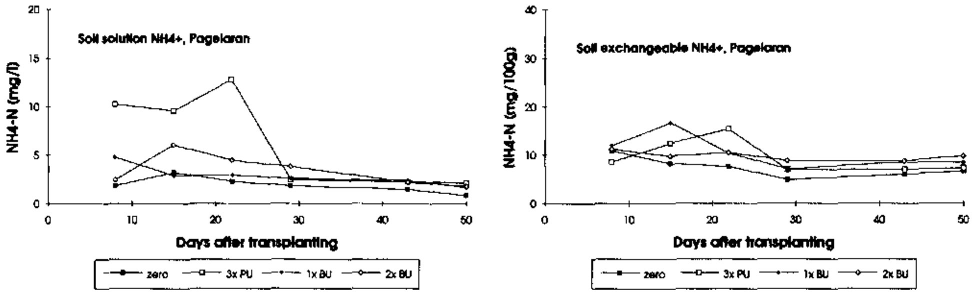
Table 2. Timing and amount of fertilizer N dressing in four treatments, for all experiment sites.

No.	N (kg/ha) applied at			N source
	7 DAT	21 DAT	42 DAT	
T1	-	-	-	-
T2	30	30	30	prilled urea
T3	90	-	-	urea briquets
T4	45	45	-	urea briquets

Results and Discussion

Soil ammonium

Time series of soil ammonium concentrations are listed in Table 3 and plotted in Figure 1. The total amounts of ammonium in solution and in the adsorbed phase (kg N/ha) can be estimated from these observations by using an average soil water content of 1 g water per g dry soil as an approximation for all flooded puddled rice soils. It is then concluded that the total amount (kg N/ha) of exchangable NH_4^+ was generally one to two orders of magnitude higher than the amount present in the soil solution. The highest adsorption per unit soil mass was found at Cianjur for the Vertisol which also showed the highest CEC value and organic matter content (Table 1). At the Citayam and Rengasdenklok sites (both clay soils), the amount of ammonium in the adsorbed phase was rather constant but a steady decrease was observed in the solution phase as time proceeded. This demonstrates that the use of a single adsorption isotherm to relate both phases during the entire growing season in lowland rice may be risky.



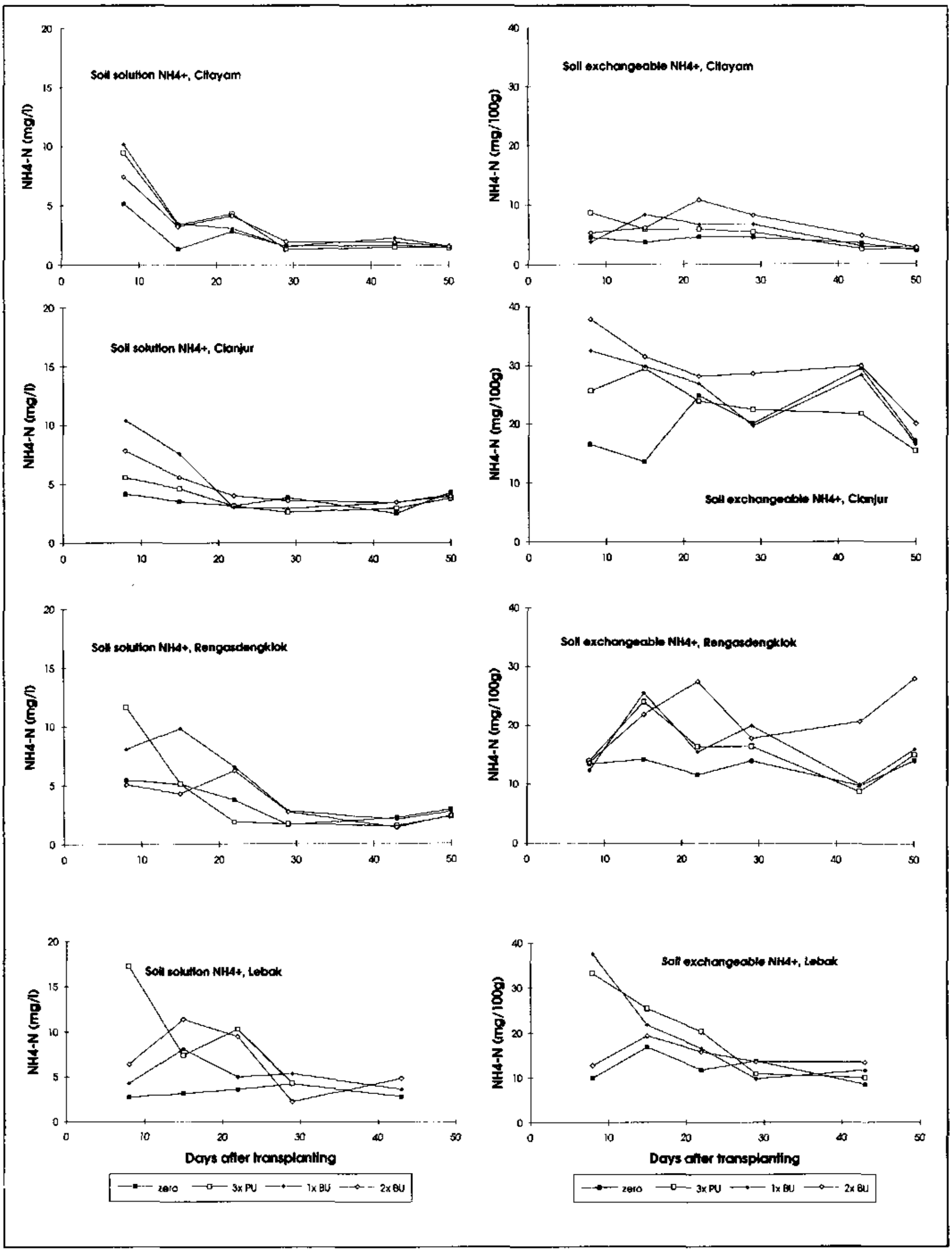


Figure 1a-1j. Availability of ammonium in soil solution and in adsorbed phase, measured on five soil types under rice cvar IR64 in West Java, for different N application methods, rainy season 1991-1992. PU = prilled urea; BU = briquet urea.

Figure 2 merges all observations of NH_4^+ concentrations in soil solution and in the adsorbed phase. Although no good relation between the two variables was found for any of the five soil types, the figure demonstrates that the soils each behaved differently with respect to the adsorption ratio, i.e. amount of NH_4^+ adsorbed vs amount in solution.

Figure 3 summarizes the observed ammonium values per treatment. Concentrations in the control plots, both in solution and in adsorbed phase, were stable. The increase of concentration in the adsorbed phase observed at Cianjur as time proceeded suggests that more ammonium was released by the soil than could be absorbed by the crop. In treatment T2 which received broadcast urea (3 splits) the time course of soil ammonium concentration in both phases varied between soils, some soils showing an early increase in adsorbed ammonium, others a decrease (Citayam and Lebak). Application of the third split of prilled urea (42 DAT) was not followed - possibly due to fast uptake - by an increase in soil ammonium except at Rengasdengklok. The latter increase, however, was observed in the other treatments in Rengasdengklok as well and is therefore not ascribed to N application. Patterns of soil ammonium in T3 and T4 were similar, but again differed considerably between soils. In T4 ammonium levels were more stable, notably at the Lebak site. This was earlier reported by Sismiyati et al. (1985). Split (2×) briquette application resulted in slightly higher soil ammonium levels than split (3×) prilled urea. This confirms claims that less nitrogen is lost when inserted into the anaerobic layer (e.g. Hong, 1976). Treatment means and standard deviations of concentrations in solution and absorbed phase are also listed in Table 3.

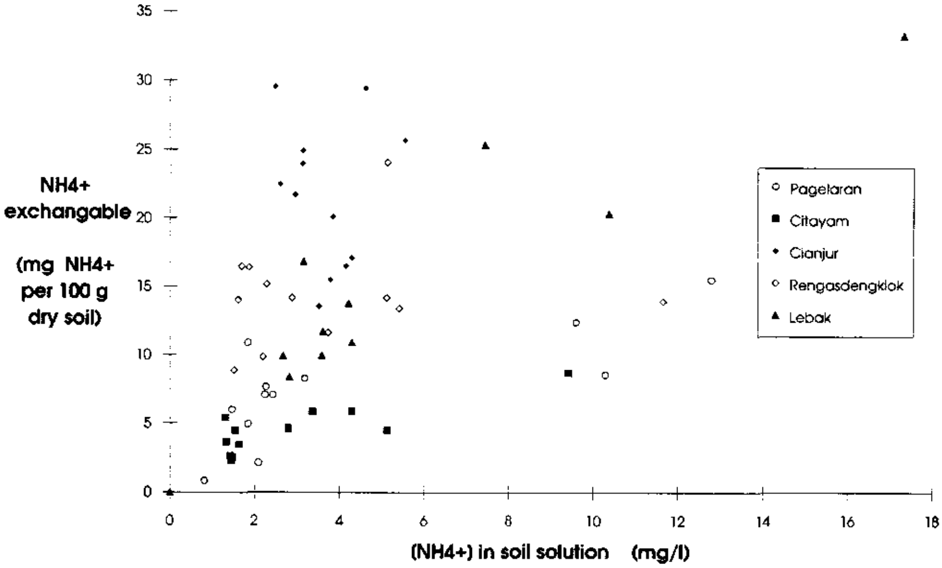


Figure 2. Relation between ammonium concentration in soil solution and in adsorbed phase for five flooded rice soils in West Java under rice cvar IR64, rainy season 1991-1992.

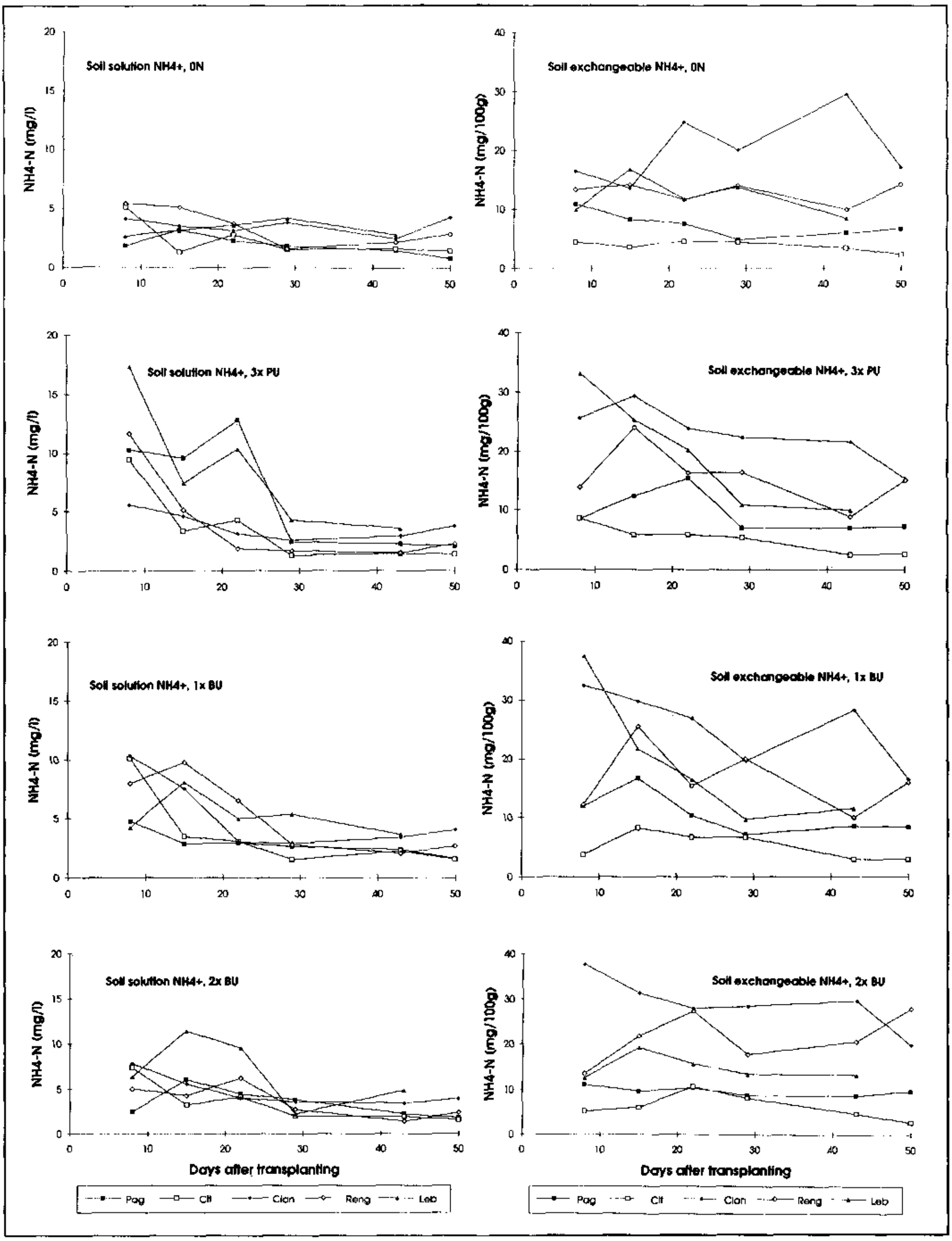


Figure 3a-3h. Availability of ammonium in soil solution and in adsorbed phase, measured for different N application methods, on five soil types under rice cvar IR64 in West Java, rainy season 1991-1992. PU = prilled urea; BU = briquet urea. For site name abbreviations see text.

Table 3. Effect of N application method on ammonium contents measured in soil solution (S) and in adsorbed phase (E) under rice cvar IR64 on five soil types in West Java, rainy season 1991-1992. (s.d. : standard deviation). Treatment codes are explained in Table 2.

DAT	Treatment	Pagelaran				Citayam			
		S		E		S		E	
		mg/l	s.d.	mg/100 g	s.d.	mg/l	s.d.	mg/100 g	s.d.
8	T1	1.85	0.41	10.86	3.11	5.13	2.09	4.48	1.19
	T2	10.29	0.58	8.50	4.20	9.42	4.48	8.65	4.20
	T3	4.79	1.43	11.96	2.84	10.15	2.44	3.68	0.71
	T4	2.45	0.50	11.21	2.86	7.42	1.00	5.27	2.02
15	T1	3.20	0.00	8.24	3.13	1.33	0.60	3.64	1.21
	T2	9.59	4.71	12.38	2.90	3.37	0.16	5.83	2.28
	T3	2.87	0.66	16.73	4.90	3.49	1.29	8.26	6.67
	T4	6.08	1.78	9.76	1.88	3.24	0.62	6.09	3.56
22	T1	2.29	0.54	7.61	1.32	2.80	0.96	4.58	0.67
	T2	12.79	5.26	15.46	2.05	4.28	1.83	5.87	0.60
	T3	2.95	0.53	10.41	0.65	3.06	0.28	6.71	0.24
	T4	4.46	1.94	10.50	4.00	4.10	0.61	10.82	5.38
29	T1	1.85	1.11	4.91	1.16	1.55	0.17	4.46	1.48
	T2	2.45	0.14	7.02	1.35	1.31	0.31	5.39	0.95
	T3	2.62	1.02	7.12	0.57	1.54	0.26	6.70	0.89
	T4	3.83	0.76	8.81	1.16	1.95	0.76	8.23	3.89
43	T1	1.47	0.26	5.96	0.84	1.64	0.15	3.44	0.80
	T2	2.27	0.92	7.02	2.75	1.48	0.25	2.50	0.24
	T3	2.38	0.59	8.55	0.35	2.25	0.38	2.92	0.32
	T4	2.20	0.76	8.77	1.48	1.91	0.60	4.66	1.62
50	T1	0.82	0.71	6.63	1.29	1.46	0.21	2.31	0.90
	T2	2.11	0.23	7.29	2.29	1.42	0.32	2.61	1.03
	T3	1.64	0.15	8.97	0.70	1.56	0.40	2.91	0.90
	T4	1.77	0.03	9.82	2.77	1.54	0.15	2.71	0.23

Table 3 continued next page

Table 3 continued

DAT	Treatment	Cianjur				Rengasdengklok			
		S		E		S		E	
		mg/l	s.d.	mg/100 g	s.d.	mg/l	s.d.	mg/100 g	s.d.
8	T1	4.15	0.41	16.49	6.66	5.41	3.10	13.38	2.80
	T2	5.55	2.58	25.64	6.98	11.65	2.36	13.92	2.87
	T3	10.37	4.17	32.48	4.03	8.03	2.17	12.25	4.06
	T4	7.82	2.62	37.84	4.25	5.05	1.30	13.60	3.57
15	T1	3.52	1.05	13.54	6.35	5.11	1.14	14.17	8.73
	T2	4.61	1.76	29.41	10.8	5.12	1.12	24.02	4.18
	T3	7.57	1.60	29.81	5.48	9.79	4.60	25.55	3.91
	T4	5.59	0.89	31.49	6.97	4.28	2.35	21.91	2.47
22	T1	3.13	0.37	24.86	8.69	3.73	0.98	11.63	2.21
	T2	3.13	0.54	23.93	6.13	1.87	0.43	16.39	10.88
	T3	3.02	0.47	26.90	6.37	6.53	5.67	15.48	3.14
	T4	4.02	0.60	28.15	2.39	6.22	3.91	27.55	17.59
29	T1	3.84	1.65	20.08	1.58	1.61	0.48	14.03	0.18
	T2	2.60	0.37	22.42	3.76	1.69	0.55	16.49	5.39
	T3	2.90	0.60	19.69	1.14	2.78	1.66	20.02	10.66
	T4	3.58	0.60	28.65	4.90	2.71	0.79	17.86	4.90
43	T1	2.49	0.83	29.53	3.66	2.21	0.41	9.84	1.75
	T2	2.95	0.47	21.67	2.56	1.52	0.25	8.84	0.55
	T3	3.43	0.58	28.31	6.07	2.07	1.18	10.02	2.20
	T4	3.44	0.07	29.92	2.86	1.38	0.23	20.79	5.46
50	T1	4.28	1.29	17.08	0.56	2.89	0.56	14.16	2.54
	T2	3.78	0.54	15.47	0.67	2.29	0.34	15.15	4.38
	T3	4.07	1.07	16.59	1.63	2.69	0.48	16.07	0.68
	T4	3.94	0.92	20.07	2.74	2.36	0.54	28.16	8.54

Table 3 continued next page

Table 3 continued

DAT	Treatment	Lebak			
		S		E	
		mg/l	s.d.	mg/100 g	s.d.
8	T1	2.68	0.70	9.90	3.11
	T2	17.32	12.32	33.22	6.69
	T3	4.24	0.92	37.54	29.10
	T4	6.39	1.17	12.72	0.27
15	T1	3.15	0.46	16.80	5.41
	T2	7.43	1.55	25.35	3.57
	T3	8.13	1.04	21.75	1.31
	T4	11.42	3.53	19.36	1.30
22	T1	3.61	0.32	11.71	2.56
	T2	10.36	5.00	20.30	1.43
	T3	5.01	0.53	16.54	0.92
	T4	9.52	5.56	15.80	1.58
29	T1	4.21	3.32	13.78	3.47
	T2	4.29	1.13	10.88	1.07
	T3	5.38	0.69	9.74	5.20
	T4	2.20	0.39	13.58	2.24
43	T1	2.83	0.21	8.37	1.58
	T2	3.59	0.46	9.97	1.90
	T3	3.66	0.54	11.62	1.38
	T4	4.88	0.64	13.42	2.41
50	T1	Not det.			
	T2	Not det.			
	T3	Not det.			
	T4	Not. det.			

Table 4. Effect of N application method on biomass of grain and straw, N contents of grain and straw, total N uptake, and apparent N recovery on five soil types in West Java, under rice cvar IR64, rainy season 1991 - 1992. Treatment codes are explained in Table 2.

Location	Treatment	Straw biomass	Grain biomass	N in straw	N in grain	Total N in above ground biomass	N Recovery
		(kg/ha)		(%)		(kg/ha)	(%)
Pagelaran	T1	1833 C[a]	1850	0.74	1.08	33.9	-
	T2	3798 AB	5032	0.91	1.41	105.3	79
	T3	3992 AB	5950	0.85	1.20	105.4	79
	T4	4291 AB	6272	0.88	1.19	112.7	87
Citayam	T1	2715 D	2167	0.80	1.05	44.3	-
	T2	5652 BC	4200	0.64	1.08	81.4	42
	T3	6434 AB	4883	0.66	1.09	95.7	57
	T4	6591 AB	5733	0.61	1.12	104.5	67
Cianjur	T1	5914 AB	5742	0.70	1.16	111.8	-
	T2	5214 B	6456	0.74	1.25	134.6	25
	T3	6093 AB	6452	0.74	1.12	116.7	5
	T4	7819 AB	7711	0.92	1.24	159.1	53
Rengasdengklok	T1	5055 A	5747	0.73	1.02	95.5	-
	T2	6061 A	5312	0.96	1.12	117.7	25
	T3	4844 A	5284	0.83	1.42	115.2	22
	T4	4997 A	6503	0.82	1.46	135.9	45
Lebak	T1	3603 B	4344	0.60	0.86	58.9	-
	T2	3974 B	6578	0.59	1.01	90.6	35
	T3	6461 A	6478	0.70	1.05	106.8	53
	T4	6598 A	6667	0.56	1.00	103.0	49

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[a] Means followed by a common letter are not significantly at the 5% level according to Duncan's Multiple Range Test.

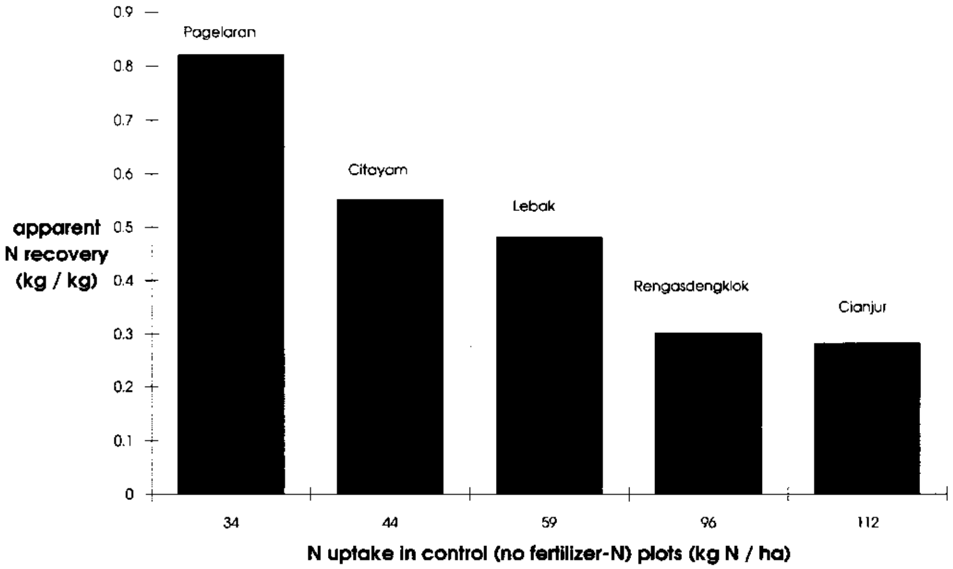

Figure 4. Recovery of fertilizer N (averaged over all treatments that received urea-N) versus native soil fertility expressed as N uptake from control plots. West Java, rice cvar IR64, rainy season 1991-1992.

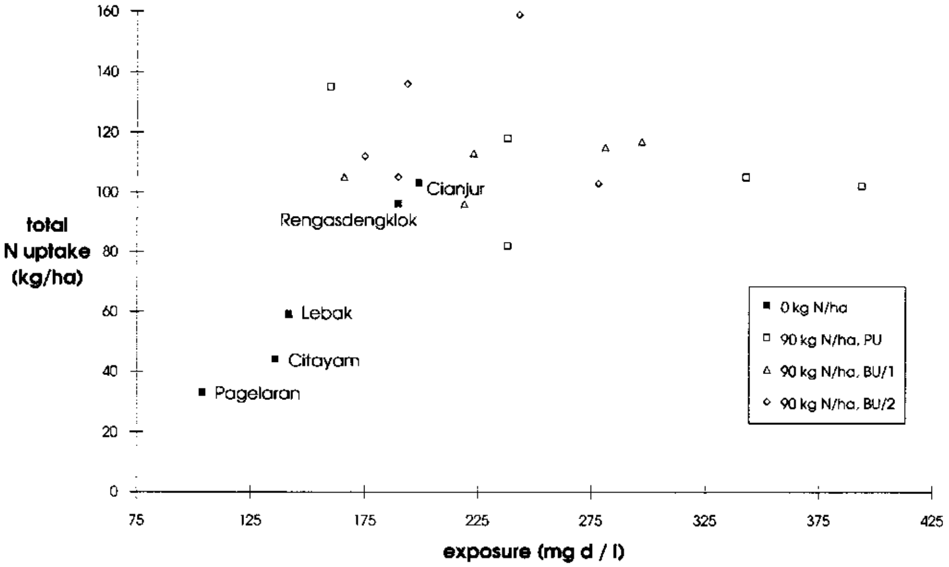

Figure 5. N uptake versus cumulative exposure of the root system to ammonium in soil solution, for five sites in West Java, rice cvar IR64, rainy season 1991-1992.
PU = prilled urea; BU = briquet urea

N uptake

The effects of N application on N contents of straw and grains are shown in Table 4. N application increased N uptake in all cases except in one treatment (T3) at the very fertile Cianjur site. Nevertheless, a strong negative correlation (r^2=0.88) was found between ANR (averaged over Treatments T2, T3, and T4) and N uptake in the control treatment (Figure 4). The highest ANR was found in the Pegalaran Regosol, the lowest in the Cianjur Vertisol.

N uptake from control (T1) plots was lowest in the Pagelaran Regosol and the Citayam Ferralsol. This coincided with low soil [NH_4^+] both in solution and in adsorbed phase (Figure 1) throughout the entire season. The highest uptake from control plots was found at Cianjur, where [NH_4^+] in solution was comparable with that found for the Lebak soil. The higher uptake at Cianjur may, however, be explained from the absence at this site of a decrease in [NH_4^+] at the end of the 50 d monitoring interval. It seems from this comparison across the five soils that the [NH_4^+] level in soil solution is a good index for ranking soils with respect to N uptake from unfertilized plots.

Solution [NH_4^+] may be less suitable as an index for absolute assessment of N uptake, especially when fertilizer was applied. We define the cumulative exposure (mg.d/l) of the crop's root system to mineral N as value of [NH_4^+] in solution integrated over time. The relation between this variable and total N uptake at harvest is given in Figure 5 for all sites and treatments. Although exposure - according to this definition - varied widely across treatments and sites, N uptake variation was limited and uptake showed no relation with exposure. Spatial heterogeneity of fertilizer application and variable proximity of urea granules to solution samplers may have caused the observed scatter. An exception to this lack of correlation between exposure and uptake can be observed for the unfertilized plots. There a very marked relation is found (Figure 5, solid symbols).

The results presented in Figures 4 and 5 indicate that factors other than N availabilty may have affected N uptake. The apparent presence of a common plateau value of 110 kg N/ha suggests that uptake was limited by a constraint common to all sites. The most likely rainy season constraint is radiation.

Biomass and yield

The effects of N application on biomass are listed in Table 4. Total aboveground biomass and grain biomass were highest in Treatment T4 on all soil types. The same was true for total N uptake, except at Lebak where uptake in Treatment T4 was marginally lower than in T3. The total biomass vs N uptake, and grain yield vs N uptake relations are shown in Figure 6 for all soil types and treatments.

Yield components are given in Table 5. The yield increase associated with N application was in most cases the result of an increase in the number of productive panicles per hill, except at the Lebak site where the number of spikelets per panicle, and the percentage of filled grains could explain the increase in yield.

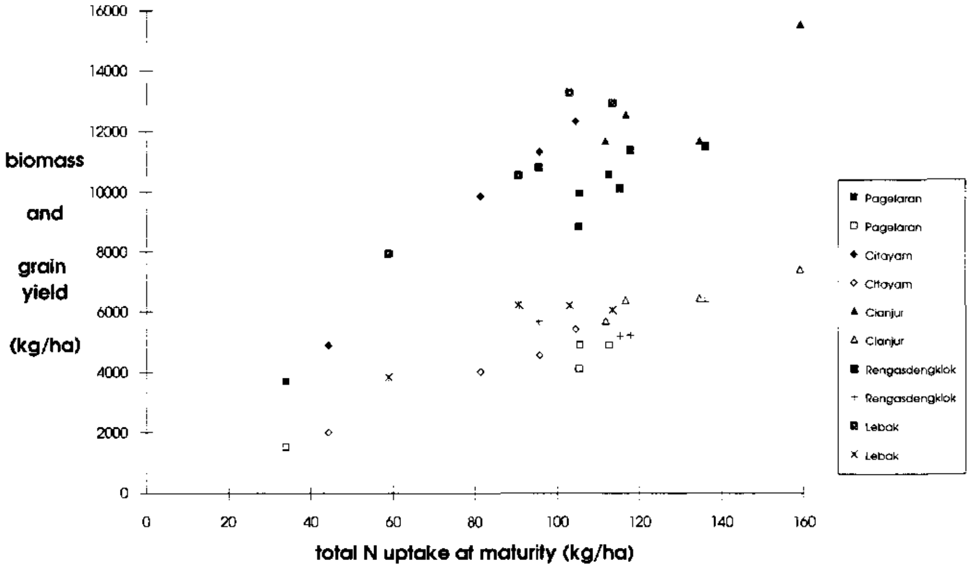

Figure 6. Total biomass (solid symbols) at maturity and grain yield (open symbols), versus total crop N uptake at maturity, for five sites in West Java, rice cvar IR64, rainy season 1991-1992.

Conclusions

N uptake and yields were generally highest on the Cianjur Vertisol. This soil, compared to the other four soils included in this study, is characterized by the highest organic matter content, soil N content, and CEC. For the unfertilized plots, the superiority of this soil over the other four soils can be explained on the basis of the observed solution [NH_4^+], which can be interpreted as lumped expression of inherent soil N fertility under given management practices. This may be a suitable, albeit laborious to determine and hard to standardize, index of native soil fertility.

For the treatments that received fertilizer-N, however, N uptake across soils and treatments was not closely related to exposure, a variable we defined to quantify a season average of ammonium availability in soil solution. This variable was high, for example, at the Pagelaran and Lebak sites where uptake was comparatively low. It cannot be concluded from this study whether this lack of relation between uptake and exposure is to be attributed to the different availabilities across soil types of nutrients other than nitrogen, to soil dependent rooting patterns or root functioning, or to different climatic conditions.

Table 5. Effect of N application method on yield and yield components of rice cvar IR64 on five soils in West Java, rainy season 1991-1992. Treatment codes are explained in Table 2.

Location	Treatment	Grain yield m.c. 14%	Yield components			
			No. of panicle/ hill	No. of grains/ panicle	Weight of 1000 kernels	Filled grains percentage
		(kg/ha)			(g)	(%)
Pagelaran	T1	1510	13.2	66	27.2	76.8
	T2	4099	11.2	70	29.0	70.0
	T3	4889	14.6	83	27.7	75.6
	T4	4874	15.9	84	26.9	70.8
Citayam	T1	2002	9.7	52	27.4	84.7
	T2	4016	9.3	58	28.4	84.9
	T3	4547	14.7	57	28.7	81.6
	T4	5413	12.7	65	29.3	78.6
Cianjur	T1	5689	11.3	54	27.5	91.4
	T2	6450	16.7	79	27.7	89.7
	T3	6380	16.3	82	27.7	89.0
	T4	7409	16.0	76	27.6	87.9
Rengasdengklok	T1	5683	10.2	83	28.6	98.9
	T2	5233	11.5	82	29.2	98.5
	T3	5194	14.4	89	28.5	98.3
	T4	6350	14.4	96	28.3	97.7
Lebak	T1	3828	15.6	95	27.1	83.3
	T2	6228	13.0	106	26.9	85.9
	T3	6050	15.1	98	27.7	85.1
	T4	6205	14.6	100	28.0	88.2

Application of urea increased ammonium concentrations in solution and in the adsorbed phase. The concentration in solution remained above the reference (control treatment) level during approximately four weeks at all sites. In the adsorbed phase, ammonium levels remained elevated throughout the duration of monitoring, except at Citayam.

Application of fertilizer N increased N uptake and grain yields and biomass in all treatment on all sites. The maximum yields and biomass were attained in the treatment where briquette urea was supplied in two splits. Differences in N uptake and yield, however, between treatments that received N were small. It is suggested that the potential for increased production arising from increased N uptake was not fully expressed due to the relatively low radiation levels in the rainy season. Further analysis with the help of simulation models is needed to support this assumption.

The direct implication of the above results is that recommended N fertilizer application levels should complement native soil N supply to match an N uptake of approximately 100 kg N/ha. This would lead to widely different N application levels for the different soil types.

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The effect of drainage, plant density and nitrogen application rate on nitrogen uptake, growth and yield of irrigated lowland rice

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Summary

Three field experiments were conducted at the Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India to study the effects of drainage, plant density and nitrogen (N) application rate on N uptake, growth and yield of irrigated lowland rice. The treatments in Experiments 1 and 2 consisted of two levels of drainage (with and without drainage), two levels of plant density (66.7 and 80 hills m^{-2}) and three levels of N (100, 150 and 200 kg ha^{-1}). Experiment 3 focused on the effect of drainage on root development. The effect of drainage on rice growth and yield was distinct. Drainage prolonged the activity of roots, which in turn delayed leaf senescence and increased remobilization of stem reserves. Grain yield increase was mainly due to an increased number of filled grains per unit area. A higher plant density had no beneficial effect on grain yield. Higher N application rates (150-200 kg N ha^{-1}) increased grain yields only in case adequate drainage was provided. Beneficial effects of drainage on root length, weight and activity were not visible in the early stages of crop growth, but became very clear after panicle initiation.

Introduction

High fertilizer inputs and improved cultural practices have shown to be very effective in raising the yield potential of irrigated lowland rice cultivars in Japan and Taiwan (Dakshinamurthi et al., 1973). Part of this success may be attributed to the construction of separate drainage channels parallel to irrigation channels in those countries (Fakuda, 1972 and Wang, 1973). The high rice yields obtained in Anamalai, a rice pocket in Tamil Nadu, India may also be partly explained by natural field drainage as a result of a sloping topography. Japanese researchers suggest a percolation rate of 10-25 mm d^{-1} to remove toxic substances from the root zone (De Datta, 1981, Hasegawa et al., 1985), especially for heavy clay soils, rich in organic matter. The possible benefits of higher percolation rates to rice growth are thought to be through the removal of phytotoxins from the root zone

(Govindasamy and Chandrasekaran, 1979; Patel and Ghildyal, 1980), increase in the O_2 concentration in the rhizosphere and an associated increase in root activity (Alva and Peterson, 1979).

In the traditional rice belt of Tamil Nadu, the Cauvery delta, soils are generally of heavy texture and poorly drained. Increasing plant density or nitrogen (N) levels beyond State recommended levels usually does not result in any yield increase. Higher N application rates often only increase the percentage of chaffy grains. Enhancing the plant density may lead to a build-up of pests and diseases and complete chaffiness of the panicles.

The objectives of this study were to determine the effect of drainage, high N application rates and a high plant density on rice growth and yield in the Cauvery delta. A separate experiment focused on the effect of drainage on root development.

Materials and methods

Field experiments were conducted at the Tamil Nadu Agricultural University (11°N, 77°E), Coimbatore, India in 1991 and 1992. The soils of the experimental fields are loamy clay soils (40% clay, 22% silt, 22% fine sand, 16% coarse sand) with low available N and high P and K contents.

Experiment 1 focused on the interaction between drainage, plant density and nitrogen application rate. Two levels of drainage were imposed: DN: no drainage and DW: with drainage. For Dw, an open drainage system around the experimental field was built, to a width and depth of 60 cm, to increase percolation and lateral movement of standing water.

Two plant densities of rice cultivar IR50 were established: P1 (67 hills m^{-2} with a plant spacing of 15 × 10 cm, conform State recommendation) and P2 (80 hills m^{-2} with a plant spacing of 12.5 × 10 cm). Nitrogen was applied at three different rates: N1 (100 kg N/ha), N2 (150 kg N/ha) and N3 (200 kg N/ha) as prilled urea, 50% at basal, 25% at 15 DAT and the remaining 25% at 30 DAT. Other nutrients applied basally were P_2O_5 and K_2O, 50 kg/ha each, and 25 kg/ha $ZnSO_4$. Green manure (Sesbania rostrata) was applied uniformly and incorporated before transplanting at 12.5 t fresh weight/ha, roughly corresponding to 75 kg N/ha. A factorial split plot design with four replications was used. Total number of subplots was 48. Subplot size was 6 m × 2.5 m. Experiment 1 was conducted in 1991 and was repeated in 1992 (Experiment 2).

Experiment 3 focused on the effect of drainage on root development. Above ground dry matter data are not reported here (see Ramasamy, 1992). The treatments comprised drainage (DW) and no-drainage (DN) in combination with 120 kg N/ha (60 kg N/ha at basal, 30 kg N/ha at 20 DAT and 30 kg N/ha at 40 DAT) or 150 kg N/ha (an additional 30 kg N/ha at heading). Rice cultivar IR20 was used. Nutrients other than N were applied as in Experiments 1 and 2, including the green manure addition before transplanting. A completely randomized block design with five replications was used. Adequate plant protection measures were taken throughout all three experiments to avoid any incidence of pests and diseases.

The rate of water percolation was determined by inserting a PVC tube, 30 cm in diameter and 60 cm in height into the plot, to a depth of 30 cm. Water was added to the tubes and the difference in water height in each column was determined at 24 hours interval. Percolation rate was calculated taking into account losses due to evaporation.

Irrigation was provided daily to keep a level of 5 cm ponded water in all plots in all 3 experiments until 7 days before harvest. The sampling area for final harvest comprised the entire plot, excluding border rows and rows used for periodical sampling. Plants were threshed, grain moisture content was measured and grain yields were computed at 14% moisture content.

Observations on dry weight of plant organs (roots, stems, green leaves, dead leaves and panicles) were conducted at 10 days intervals starting from 20 DAT. Five plants from sample rows along with roots were removed carefully from each plot, cleaned and dried at 80°C for 72 hours. Leaf area was measured using a leaf area meter (Model Li-3100 Li-Cor Inc., Nebraska, USA). Nitrogen content was estimated using the micro-Kjeldahl method (Humphries, 1956). The number of productive tillers per hill was determined at harvest from 10 hills. Panicles obtained from the productive tillers were threshed, and filled and non-filled grains were counted; 1000 grain weight was determined for each plot and corrected to 14% moisture content.

Roots were washed, first in running water and then in distilled water and detached from their nodal bases. The volume of roots was measured by the volume displacement method, after removing excess moisture on the root surface. The length and weight of 10 randomly selected roots was measured. Total root length per plant was derived from this subsample and total root weight. The diameter of roots from the third, fifth and seventh nodes of the culm were measured, 3.0 cm away from the base using a 'screw gauge'.

Based on the colour of the roots, roots were separated into active (white), moderately active (brown) and less active (black), as suggested by Cheng (1983). The proportion of different coloured roots was counted at various growth stages and expressed as a percentage of the total number of roots.

The oxidizing activity of roots was determined by measuring oxidation of alpha naphthylamine (α-NA). The α-NA oxidation is related to the rate of respiration (Ota, 1970). One gram of fresh roots was transferred into a 150 ml flask containing 50 ml of 20 ppm α-NA. The flasks were incubated for two hours at room temperature in an end-over-end shaker. After incubation, the aliquots were filtered and 2 ml of aliquot was mixed with 1 ml $NaNO_3$ (100 ppm) and 1 ml sulphanilic acid to develop the colour.

Results and discussion

Dates of sowing, transplanting, harvest and phenological events in the three experiments are summarized in Table 1. Percolation rates in the no-drainage plots for all experiments were on average about 3 mm d^{-1}. With drainage, percolation rates increased to 12 - 14 mm d^{-1}.

Table 1. Dates of phenological events in the three field experiments conducted at Coimbatore, India. Experiments 1 and 2: cv. IR50, Experiment 3: cv. IR20.

Growth stage	Date Exp. 1	DAT	Date Exp. 2	DAT	Date Exp. 3	DAT
Sowing	19-6-1990	-	27-5-1991	-	30-11-1991	-
Transplanting	13-7-1990	-	19-6-1991	-	26-12-1991	-
Pan. initiation	11-8-1990	30	18-7-1991	30	21-02-1992	58
Flowering	08-9-1990	57	17-8-1991	60	23-03-1992	88
Harvest	9-10-1990	88	18-9-1991	91	22-04-1992	118

Biomass partitioning (Experiments 1 and 2)

Total biomass of green leaves and leaf area index (LAI) increased during the vegetative phase and decreased after flowering (Table 2). Differences between drainage and no-drainage plots were only visible during the later part of crop growth. Senescence was hastened in the no-drainage plots (Table 2). A higher plant density (P2) resulted initially in a greater biomass of green leaves and higher LAI than in P1 in Experiment 1. Differences vanished at 50 DAT. N application rates higher than the recommended 100 kg N/ha increased green leaf production and LAI from the beginning of the crop growth and delayed senescence up to flowering.

Before heading, stem weight increased for all treatments, indicating that a considerable amount of starch and sugars accumulated in the stem and leaf sheaths. After heading, stem weights decreased until maturity. Yoshida (1981) attributed similar observations to remobilization of carbohydrates. Most of the stored carbohydrates are redistributed to the panicles. The contribution of accumulated carbohydrates to grain carbohydrates normally ranges from 0 to 40% depending on the rate of N applied and the growth duration. According to Penning de Vries et al. (1989), 20% or more of the weight of vegetative organs may consist of remobilizable starch, particularly in cereals. Lower stem weights in the drainage plots at the time of harvest in both Experiments 1 and 2 may be attributed to better remobilization. The remobilization in drainage plots is related to a better root activity which will be discussed below. The translocation of stored reserves from the stem and leaf sheaths was less pronounced in the N3 plots (Table 2).

Root weights increased up to heading and were greater under drainage conditions (Dw), probably due to a larger root volume and thicker roots. Root weights varied on a per hill basis. Wider spacing resulted in higher root weight per hill, but total root weight per unit area was constant. Rakheniov and Gol'fand (1979) also observed no variation in root volume for different plant densities per unit area.

Table 2. Dry weight of plant organs (kg/ha) and leaf area index (LAI) at different days after transplanting (DAT) for field Experiments 1 and 2 conducted at Coimbatore, India (cv. IR50). DW = with drainage, DN = without drainage, P1 = 67 hills m^{-2}, P2 = 80 hills m^{-2}, N1 = 100 kg N ha^{-1}, N2 = 150 kg N ha^{-1}, N3 = 200 kg N ha^{-1}.

Dry weight green leaves (kg/ha) - Experiment 1

DAT	DN	DW	P1	P2	N1	N2	N3
30	805	827	773	859	771	819	858
40	1248	1343	1228	1363	1164	1285	1437
50	2033	2042	1972	2103	1809	2080	2248
60	2136	2184	2080	2240	1961	2213	2306
70	1887	2162	1961	2089	1870	2077	2119
80	1097	1293	1223	1167	1048	1224	1325
88	290	790	571	509	416	525	679

Dry weight dead leaves (kg/ha) - Experiment 1

DAT	DN	DW	P1	P2	N1	N2	N3
60	287	253	229	310	259	274	295
70	678	486	559	605	567	568	584
80	1437	1320	1273	1484	1355	1396	1385
88	2162	1792	1865	2090	1888	2026	2018

Dry weight stems (kg/ha) - Experiment 1

DAT	DN	DW	P1	P2	N1	N2	N3
30	773	786	721	839	745	784	812
40	2094	2168	2002	2260	1989	2141	2263
50	3765	3722	3704	3786	3277	3765	4189
60	4714	4765	4642	4839	4252	4828	5139
70	5107	5286	5161	5231	4400	5588	5601
80	4252	4031	4230	4053	3751	4285	4389
88	2859	2624	2692	2791	2631	2752	2841

Table 2 continued next page

Table 2 continued

Dry weight roots (kg/ha) - Experiment 1

DAT	DN	DW	P1	P2	N1	N2	N3
30	447	405	423	489	445	456	466
40	1039	1054	961	1133	1024	1044	1072
50	1369	1471	1313	1528	1357	1435	1469
60	1530	1598	1485	1643	1489	1564	1639
70	1469	1604	1498	1575	1479	1552	1579
80	1359	1505	1379	1485	1382	1437	1477
88	1137	1367	1164	1340	1180	1281	1295

Dry weight panicles (kg/ha) - Experiment 1

60	1213	1200	1104	1308	1169	1411	1231
70	4149	3052	3631	3570	3704	3425	3707
80	6005	6451	6305	6161	5914	6248	6514
88	7862	8347	8378	7830	7575	8206	8527

LAI - Experiment 1

DAT	DN	DW	P1	P2	N1	N2	N3
30	2.7	2.71	2.52	2.89	2.52	2.76	2.84
40	4.3	3.93	3.86	4.36	3.73	4.21	4.65
50	6.59	6.51	6.31	6.79	5.79	6.76	7.1
60	6.84	6.97	6.66	7.15	6.25	7.08	7.38
70	5.76	6.6	5.99	6.37	5.73	6.34	6.46
80	3.4	3.93	3.71	3.62	3.22	3.8	4.11
88	0.9	2.45	1.77	1.58	1.29	1.63	2.11

Dry weight green leaves (kg/ha) - Experiment 2

DAT	DN	DW	P1	P2	N1	N2	N3
23	732	711	715	728	679	725	757
33	1306	1213	1283	1236	1148	1263	1366
43	2021	2109	2085	2045	1835	2035	2327
53	2811	2866	2775	2902	2652	2833	3031
63	2094	2312	2144	2262	2094	2224	2292
74	1272	1777	1378	1571	1283	1539	1752
84	592	1137	918	810	765	861	968
91	246	840	542	545	465	580	659

Table 2 continued next page

Table 2 continued

Dry weight dead leaves (kg/ha) - Experiment 2

DAT	DN	DW	P1	P2	N1	N2	N3
53	134	49	104	79	81	99	94
63	882	221	538	565	565	549	540
74	1200	944	995	1146	1106	1064	1045
84	2214	1989	1938	2265	2079	2083	2143
91	2494	2271	2222	2549	2284	2363	2510

Dry weight stems (kg/ha) - Experiment 2

DAT	DN	DW	P1	P2	N1	N2	N3
23	598	577	555	620	567	591	605
33	1728	1736	1621	1843	1648	1759	1771
43	2922	2840	2658	3110	2770	2867	3007
53	4451	4439	4342	4548	4221	4453	4655
63	5570	5734	5402	5900	5365	5728	5865
74	4822	4585	4364	5043	4413	4737	4960
84	3295	3283	3092	3486	3074	3298	4427
91	2917	2687	2687	2973	2618	2841	3030

Dry weight roots (kg/ha) - Experiment 2

DAT	DN	DW	P1	P2	N1	N2	N3
23	330	334	324	339	325	333	337
33	747	731	734	744	719	737	763
43	1103	1205	1130	1178	1121	1163	1178
53	1258	1450	1349	1391	1345	1371	1395
63	1395	1593	1456	1508	1443	1474	1509
74	1394	1572	1471	1496	1456	1486	1507
84	1331	1520	1424	1426	1403	1426	1447
91	990	1284	1118	1157	1077	1159	1175

Dry weight panicles (kg/ha) - Experiment 2

53	306	166	200	250	231	204	255
63	1749	1800	1770	1815	1953	1855	1784
74	5092	5622	5632	5184	5362	5424	5276
84	6988	8321	7678	7633	7329	7802	6895
91	8073	9698	8881	8816	8496	8957	9026

Table 2 continued next page

Table 2 continued

DAT	*LAI - Experiment 2* DN	DW	P1	P2	N1	N2	N3
23	2.34	2.29	2.30	2.33	2.17	2.35	2.43
33	3.88	3.18	2.71	3.95	3.68	4.04	4.37
43	6.54	6.27	6.47	6.34	5.69	6.31	7.21
53	8.59	8.43	8.21	8.80	7.84	8.47	9.16
63	6.28	6.95	6.44	6.79	6.15	6.67	7.03
74	3.85	5.33	4.71	4.47	3.85	4.62	5.30
84	1.80	3.47	2.80	2.47	2.34	2.63	2.94
91	0.92	2.60	1.83	1.69	1.44	1.80	2.04

Root activity

Changes in the colour of roots reflect changes in their activity (Cheng, 1983) or in soil aeration (Ota, 1970). The root activity in Experiments 1 and 2 decreased fast with crop age in the no-drainage treatments, as can be seen from the percentage of white and brown roots in Table 3. With drainage, root activity continued until ripening stage in Experiment 3, as was observed from colour (Table 3), volume (Table 4), length (Table 5) and diameter (Table 6) of the roots. Drainage thickened the roots. Root diameter is related to root aeration and root activity (Yoshida, 1981). Wider root diameter, higher total root length and more volume contributed to higher root weight throughout the growth period in drainage plots. Similar results were reported by Patel and Ghildyal (1983).

In the early stage of crop growth, roots maintain their whiteness by oxidizing ferrous iron present within the root zone. The oxidizing power for drainage and no-drainage plots were similar in the early part of crop growth. At later growth stages more and more ferrous iron was fixed to the root surface, changing its colour from light brown to reddish brown due to a decrease in oxidizing power. The α-NA oxidizing power of the roots in no-drainage plots clearly fell below that of drainage plots after flowering (Table 7). The rate of dry matter production drops to zero if the root oxidizing power gets below 2 mg α-NA /hr/g root dry weight (Dai, 1988), which explains the inactiveness of roots under the no-drainage system in our study, especially after heading (Table 7). Significant differences between drained and undrained plots were observed from 62 DAT onwards, i.e. shortly after panicle initiation.

Table 3. Effect of drainage on root colour of cv. IR50 in Experiments 1 and 2, Coimbatore, India. All values are expressed as a percentage of the total number of roots. DW = with drainage, DN = without drainage, P1 = 67 hills m^{-2}, P2 = 80 hills m^{-2}, N1 = 100 kg N ha^{-1}, N2 = 150 kg N ha^{-1}, N3 = 200 kg N ha^{-1}.

Treatment	Tillering			Panicle Initiation			Heading			Milk ripening		
	White	Brwn	Black	White	Brwn	Black	White	Brwn	Black	White	Brwn	Black
	Experiment 1											
DN	12.3	70.0	17.7	4.6	59.7	35.7	0.0	57.3	42.7	0.0	32.0	68.0
DW	36.3	60.3	3.4	31.7	64.0	4.3	28.0	69.3	2.7	25.3	73.0	1.7
SE_d	(1.9)	(2.3)	(2.3)	(1.9)	(1.8)	(2.1)	(1.0)	(2.3)	(2.1)	(1.5)	(2.2)	(2.3)
CD (P=0.05)	(4.2)	(5.1)	(5.2)	(4.2)	NS	(4.8)	(2.6)	(5.1)	(4.8)	(3.4)	(5.0)	(5.1)
	Experiment 2											
DN	17.3	75.0	7.7	9.0	63.3	27.7	3.3	50.3	46.4	0.0	42.3	57.7
DW	40.0	59.3	0.7	38.5	58.4	3.1	33.4	63.6	3.0	20.4	69.3	5.3
SE_d	(1.9)	(1.9)	(1.6)	(2.1)	(1.6)	(1.8)	(1.3)	(1.5)	(1.4)	(1.0)	(0.9)	(1.1)
CD (P=0.05)	(4.3)	(4.3)	(3.6)	(4.8)	NS	(4.1)	(2.9)	(3.4)	(3.2)	(2.6)	(2.0)	(2.5)

NS = Not significant

SE_d = Standard error of difference

CD (P=0.05) = Critical difference

Table 4. Root volume of cv. IR20 (cm^3/hill) as affected by drainage and N treatment in field Experiment 3, Coimbatore, India. DW = with drainage, DW+N = with drainage + 30 kg/ha at flowering; DN = without drainage, DN+N = without drainage + 30 kg/ha at flowering.

Treatment	Days after transplanting						
	30	60	67	74	81	100	118*
DN	5.7	20.8	24.6	24.1	22.4	16.9	15.2
DN + N	5.2	20.3	23.5	23.8	23.1	17.4	15.8
DW	4.9	21.2	27.2	32.0	32.1	27.5	25.1
DW + N	5.1	20.8	26.4	31.8	32.7	28.1	25.0
SE_d	0.41	0.62	0.78	0.83	0.77	0.67	0.52
CD (P=0.05)	NS	NS	1.7	1.8	1.7	1.5	1.1

* At harvest

SE_d = standard error of difference

CD (P=0.05) = critical difference

Table 5. Root length of cv. IR20 (cm/hill) as affected by drainage and N treatment in field Experiment 3, Coimbatore, India. DW = with drainage, DW+N = with drainage + 30 kg/ha at flowering; DN = without drainage, DN+N = without drainage + 30 kg/ha at flowering.

Treatment	Days after transplanting					
	30	60	74	81	100	118*
DN	1345	5221	6361	6013	4927	4018
DN + N	1268	5320	6197	6107	4898	4113
DW	1251	5322	7992	7415	7051	6036
DW + N	1328	5218	7318	7396	7096	6030
SE_d	47	167	279	263	285	280
CD (P=0.05)	NS	NS	608	574	621	611

* At harvest

SE_d = standard error of difference

CD (P=0.05) = critical difference

Table 6. Root diameter of cv. IR20 (cm^2/hill) as affected by drainage and N treatment in field Experiment 3, Coimbatore, India. DW = with drainage, DW+N = with drainage + 30 kg/ha at flowering; DN = without drainage, DN+N = without drainage + 30 kg/ha at flowering.

Treatment	Nodal position of the root		
	3rd	5th	7th
DN	0.40	0.61	0.63
DN + N	0.39	0.62	0.65
DW	0.57	0.71	0.80
DW + N	0.53	0.72	0.78
SE_d	0.018	0.023	0.024
CD (P=0.05)	0.04	0.05	0.05

SE_d = standard error of difference

CD (P=0.05) = critical difference

Table 7. Alpha-Naphthylamine oxidation as affected by drainage and N treatment in field xperiment 3, Coimbatore, India (cv. IR20). DW = with drainage, DW+N = with drainage + 30 kg/ha at flowering; DN = without drainage, DN+N = without drainage + 30 kg/ha at flowering.

Treatments	Days after transplanting				
	0	31	62	92	118*
DN	5.04	4.99	4.12	3.1	2.1
DN + N	5.06	4.95	4	2.92	2.17
DW	5.05	4.96	5.02	4.83	4.38
DW + N	5.04	4.92	4.93	4.72	4.26
SE_d	0.09	0.072	0.074	0.067	0.052
CD (P=0.05)	NS	NS	0.16	0.15	0.11

* At harvest

SE_d = standard error of difference

CD (P=0.05) = critical difference

N content of plant organs (Experiments 1 and 2)

Nitrogen content of the green leaves in general increased after transplanting during a few weeks and then decreased gradually to a minimum at harvest (Table 8). No drainage and high N input levels resulted in a higher N content in the green leaves in the initial phases. Differences vanished towards the reproductive phase. The general increase in leaf N after transplanting might be due to a higher availability of soil N available from inorganic N topdressed at 15 and 30 DAT. The general reduction in the N content at later stages may be attributed to aging and dilution because of translocation of the element to other parts, especially to reproductive organs. The slow declining rate of N observed in drainage plots was due to better N uptake because of prolonged 'root activity' as reported earlier.

The nitrogen content of dead leaves increased as growth approached maturity, indicating an inhibition in the process of redistribution of the nitrogen to other organs (Table 8). Dead leaves have generally lost some weight, even without disease. This indicates that some fraction of biomass is used before the leaves die, either for respiration or remobilization. Both processes increase the amount of carbohydrates available for growth. It is assumed that dead leaves contribute half their original weight to the carbohydrate pool (Penning de Vries et al., 1989). In the present study, 67% leaf N was translocated under no-drainage, and 78% in drainage plots. The N content of dead leaves at the initial stages was similar for all treatments but at maturity it was lower in drainage plots than in undrained plots. Better remobilization in the beginning and only a partial remobilization at the maturity may well be linked with root activity and physiological processes. Low residual N in dead leaves in drainage plots is probably due to a better translocation.

There was an increase in stem N content during the first weeks after transplanting. The start of decline in stem N content coincided with panicle initiation, indicating translocation of N from stems to panicles. Plants in drainage plots had a higher N content than no-drainage plots at this stage, but at harvest lower N contents were recorded, indicating better translocation (Table 8).

The N content in the roots also increased in the initial growth period but afterwards it gradually decreased to a minimum at harvest (Table 8). The reduction in root N may be attributed to remobilization as well as reduced root activity due to aging as discussed before. The active root system of the drainage plots maintained the root N content at a fairly constant level probably due to better N uptake by young, new roots.

Table 8. Nitrogen content of plant organs (%) and total N uptake (kg N/ha) of cv. IR50 in field Experiments 1 and 2, Coimbatore, India. DW = with drainage, DN = without drainage, P1 = 67 hills m^{-2}, P2 = 80 hills m^{-2}, N1 = 100 kg N ha^{-1}, N2 = 150 kg N ha^{-1}, N3 = 200 kg N ha^{-1}.

N content green leaves (%) - Experiment 1

DAT	DN	DW	P1	P2	N1	N2	N3
30	2.81	2.38	2.66	2.54	2.36	2.64	2.79
40	2.51	2.24	2.45	2.3	2.13	2.46	2.53
50	2.02	1.96	2.01	1.97	1.89	2.04	2.05
60	1.76	1.7	1.74	1.72	1.54	1.84	1.81
70	1.17	1.24	1.25	1.16	1.17	1.2	1.26
80	1.05	1.13	1.13	1.05	1.08	1.09	1.1
88	0.72	1.11	0.92	0.91	0.88	0.93	0.94

N content dead leaves (%) - Experiment 1

DAT	DN	DW	P1	P2	N1	N2	N3
60	0.35	0.46	0.38	0.43	0.4	0.4	0.41
70	0.49	0.58	0.52	0.54	0.51	0.53	0.55
80	0.62	0.59	0.6	0.61	0.59	0.6	0.61
88	0.65	0.58	0.62	0.61	0.6	0.61	0.63

N content stems (%) - Experiment 1

DAT	DN	DW	P1	P2	N1	N2	N3
30	1.11	1.04	1.09	1.07	0.99	1.05	1.15
40	1.25	1.23	1.25	1.23	1.17	1.22	1.33
50	1.21	1.31	1.3	1.21	1.22	1.25	1.3
60	0.95	1.13	1.05	1.03	0.98	1.06	1.08
70	0.79	0.93	1.87	0.85	0.84	0.84	1.13
80	0.74	0.66	0.71	0.68	0.67	0.7	0.72
88	0.66	0.43	0.55	0.54	0.51	0.57	0.56

Table 8 continued next page

Table 8 continued

N content roots (%) - Experiment 1

DAT	DN	DW	P1	P2	N1	N2	N3
30	0.92	0.89	0.89	0.91	0.88	0.92	0.91
40	1	1.08	1.03	1.05	0.96	1.07	1.09
50	0.81	1.06	0.93	0.94	0.92	0.94	0.95
60	0.6	1.04	0.83	0.81	0.83	0.82	0.82
70	0.54	0.99	0.78	0.76	0.72	0.79	0.78
80	0.45	0.95	0.73	0.67	0.65	0.73	0.73
88	0.42	0.89	0.69	0.62	0.62	0.67	0.68

Total N uptake (kg/ha) - Experiment 1

DAT	DN	DW	P1	P2	N1	N2	N3
30	35.5	31.7	32.2	35	29.4	33.8	37.6
40	68.2	68.2	65.3	71.2	57.9	68.7	78
50	97.5	104.2	100	101.7	84.9	103.1	114.7
60	112.7	116.6	111.6	117.3	98.9	118.3	126.1
70	131.4	135.9	131.4	135.9	121	131.9	139.6
80	138.8	144.4	143.3	139.6	130	142.7	151.7
88	144.9	153.8	153.3	145.5	136.1	151.9	160.1

N content green leaves (%) - Experiment 2

DAT	DN	DW	P1	P2	N1	N2	N3
23	2.45	2.24	2.44	2.25	2.17	2.34	2.53
33	2.83	2.5	2.68	2.65	2.38	2.79	2.83
43	2.33	2.19	2.3	2.22	2.07	2.28	2.41
53	1.85	1.71	1.82	1.74	1.63	1.83	1.88
63	1.63	1.51	1.65	1.49	1.57	1.64	1.56
74	1.23	1.56	1.42	1.37	1.3	1.43	1.45
84	1.13	1.37	1.25	1.23	1.17	1.28	1.28
91	0.74	1	0.88	0.86	0.84	0.87	0.9

N content dead leaves (%) - Experiment 2

DAT	DN	DW	P1	P2	N1	N2	N3
53	0.3	0.3	0.3	0.3	0.3	0.3	0.3
63	0.35	0.34	0.34	0.35	0.33	0.34	0.37
74	0.47	0.41	0.45	0.44	0.43	0.43	0.47
84	0.62	0.57	0.58	0.6	0.58	0.6	0.6
91	0.68	0.61	0.58	0.6	0.63	0.64	0.67

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Table 8 continued

N content stems (%) - Experiment 2

DAT	DN	DW	P1	P2	N1	N2	N3
23	1.14	1.1	1.13	1.1	1.09	1.13	1.14
33	1.18	1.18	1.18	1.19	1.13	1.19	1.24
43	1.38	1.46	1.43	1.4	1.24	1.47	1.54
53	1.04	1.19	1.11	1.11	1.05	1.12	1.19
63	0.96	1.12	1.07	0.94	1	1.04	1.09
74	0.73	0.89	0.81	0.8	0.76	0.82	0.84
84	0.72	0.62	0.67	0.67	0.66	0.67	0.69
91	0.68	0.47	0.57	0.58	0.55	0.57	0.62

N content roots (%) - Experiment 2

DAT	DN	DW	P1	P2	N1	N2	N3
23	0.93	0.91	0.94	0.91	0.92	0.92	0.94
33	0.98	0.96	0.99	0.96	0.91	0.97	1.01
43	1.23	1.18	1.22	1.19	1.17	1.2	1.27
53	1.13	1.14	1.18	1.14	1.12	1.17	1.18
63	1.08	1.18	1.13	1.14	1.07	1.11	1.11
74	0.93	1.1	1.03	1	1	1.02	1.01
84	0.8	1.05	0.95	0.9	0.91	0.94	0.93
91	0.64	0.99	0.82	0.81	0.81	0.83	0.79

Total N uptake (kg/ha) - Experiment 2

DAT	DN	DW	P1	P2	N1	N2	N3
23	28	25.8	27.4	26.4	24.2	26.8	29.6
33	65.1	57.5	60.9	61.7	51.9	63.3	68.7
43	101.3	102.2	100.1	103.4	85.3	102.5	117.4
53	115.3	123.4	118.4	120.3	105.1	120.8	132.1
63	131.1	138.7	133.7	136	124.7	135.9	144.1
74	141.7	150.1	146.7	145	134	149.2	154.6
84	150.6	160.8	156.2	155.3	145.2	158.2	163.7
91	156.3	170.5	160.1	157.9	148.2	162.2	168.3

Nitrogen uptake

In general, N uptake continued up to maturity (Figure 1). The rate of uptake peaked at maximum tillering (30-40 DAT) and declined slowly afterwards. The rate of N uptake was higher and faster in the initial stage in case of no drainage, a high plant density and high N input level. Nitrogen uptake continued even after flowering, and was highest for drainage plots. Samantaray et al. (1990) also observed high uptake rates in the vegetative period, which they attributed to fertilizer-N and at a later stage, mineralized soil-N. Rai and Murthy (1979) on the other hand stated that greater dry matter production, LAI, stem N content and total N uptake at tillering stage may retard growth rate and N uptake at a later growth stage, as was also observed in no-drainage and higher N (200 kg N/ha) applied plots in our study.

Nitrogen translocation

In general, more than 50% of the N found in the grains and panicles resulted from photosynthesis after flowering. Nitrogen translocation from the stem was greater than from leaves (Table 9). A maximum of 80% of stored N in the stem was translocated in the drained plots. This was only 59 to 67% for the non-drained plots. Varying plant density or N input level had very little impact on N translocation. Translocation from the leaves ranged from a low 19 kg N/ha to 34 kg N/ha. The residual N percentage in dead leaves was higher in undrained plots than in drained plots. Moreover, the N content of the green leaves of drained plots was fairly high even at the time of maturity.

Grain yield and yield components (Experiments 1 and 2)

In both Experiments 1 and 2, drainage increased grain yield substantially, to a maximum of about 1.9 t/ha in Experiment 2 (Table 10). Similar beneficial effects of drainage on grain yield were reported by Ahn et al. (1991), Habibullah et al. (1977) and Iida et al. (1990).

More pronounced tillering noticed under no-drainage had no effect on the number of productive tillers (Table 11). Higher N application rates resulted in a higher number of productive tillers only in Experiment 2. Higher plant density resulted in a lower number of productive tillers per hill. However, the number of productive tillers per unit area was the same for both treatments (Table 11).

The number of spikelets per panicle was not affected by drainage. A higher plant density resulted in a lower spikelet number per panicle.

The number of filled grains per panicle was significantly altered by various treatment combinations. Drainage increased the percentage of filled grains by 14%. This percentage was still improved by higher N application rates. In case of the non-drained plots, higher N application rates only resulted in more chaffy grains and higher N uptake did not result in a higher percentage of filled grains. Absence of response to a higher N application rate may be due to increased spikelet sterility (Singh and Bhattacharjee, 1988). Balasubramanian and Palaniappan (1991) also reported a lower percentage of filled grains in non-drained plots with high N inputs.

The harvest index was improved by 7-12% by providing drainage to the root system (Table 11). A higher plant density and higher N application rate decreased harvest index by leaving a considerable portion of the N in the stem and leaves. Thousand grain weight was unaltered by drainage and density but higher N levels improved it to a small extent.

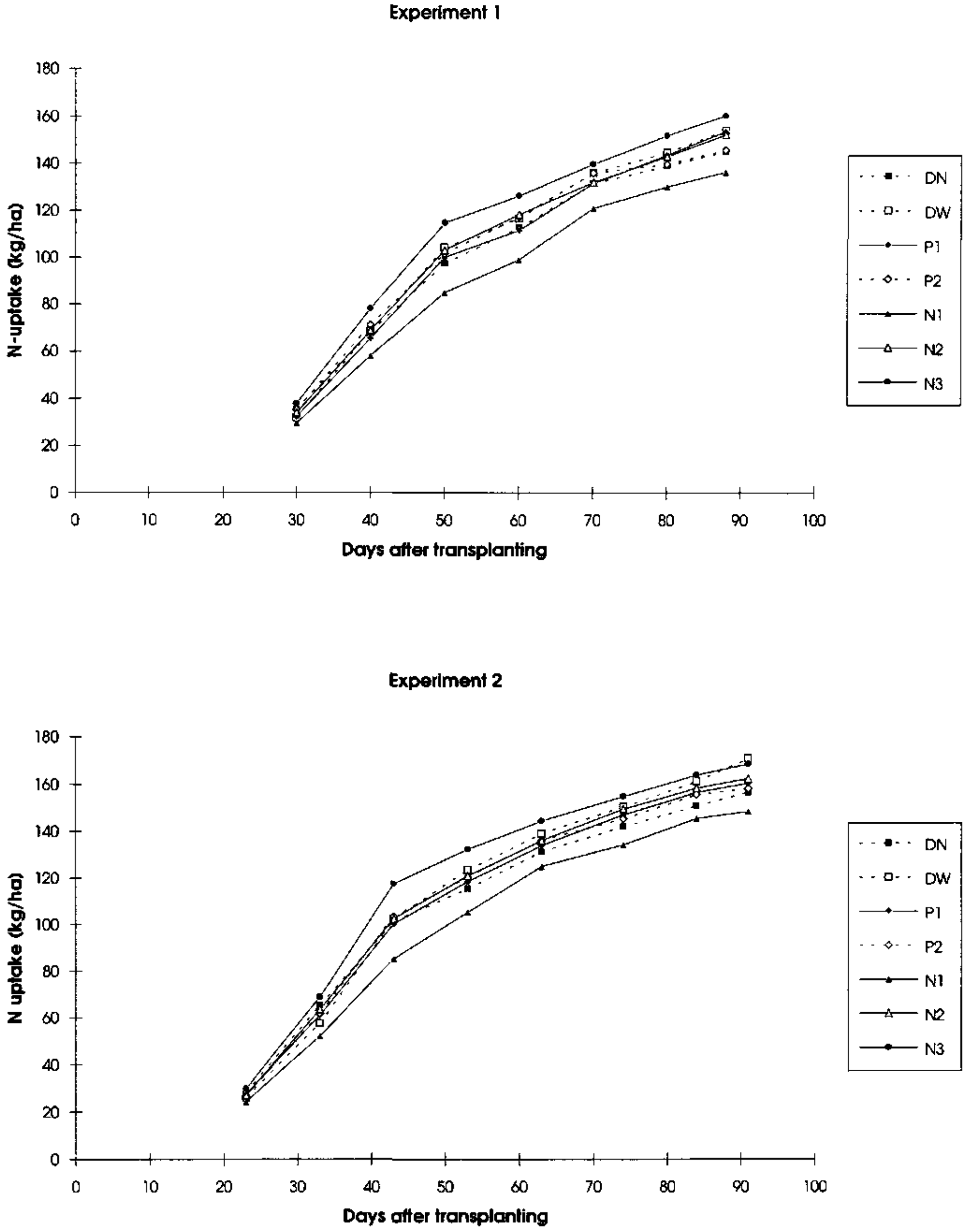

Figure 1a, 1b. Total N uptake as a function of days after transplanting (DAT) for the various treatments in Experiments 1 and 2, Coimbatore, India (cv. IR50). DW = with drainage, DN = without drainage, P1 = 67 hills m^{-2}, P2 = 80 hills m^{-2}, N1 = 100 kg N ha^{-1}, N2 = 150 kg N ha^{-1}, N3 = 200 kg N ha^{-1}.

Table 9. Total N translocated from leaf and stem to various growth organs (kg/ha) in field Experiments 1 and 2, Coimbatore, India (cv. IR50). DW = with drainage, DN = without drainage, P1 = 67 hills m^{-2}, P2 = 80 hills m^{-2}, N1 = 100 kg N ha^{-1}, N2 = 150 kg N ha^{-1}, N3 = 200 kg N ha^{-1}. Values in paranthesis are percentages of the maximum N uptake observed during the experiments.

Treatments	1990		1991	
	Stem	Leaf	Stem	Leaf
DN	26.69	24.92	35.97	33.22
	(58.60)	(60.70)	(67.30)	(63.90)
DW	42.56	20.86	51.59	26.76
	(79.00)	(52.10)	(80.30)	(54.60)
P1	33.93	22.83	42.48	32.83
	(69.20)	(57.60)	(73.50)	(5.00)
P2	34.79	24.05	38.22	30.51
	(69.80)	(58.10)	(68.90)	(60.40)
N1	28.25	19.2	39.26	24.75
	(67.80)	(56.20)	(73.20)	(57.30)
N2	35.49	25.19	43.3	31.73
	(69.30)	(59.40)	(72.80)	(61.20)
N3	39.59	26.99	45.13	34.23
	(71.30)	(58.60)	(70.60)	(60.10)

Table 10. Grain yields (kg/ha) observed for the various treatments in Experiments 1 and 2, Coimbatore, India (cv. IR50). DW = with drainage, DN = without drainage, P1 = 67 hills m^{-2}, P2 = 80 hills m^{-2}, N1 = 100 kg N ha^{-1}, N2 = 150 kg N ha^{-1}, N3 = 200 kg N ha^{-1}.

Treatment	Experiment 1				Experiment 2			
	N1	N2	N3	Mean	N1	N2	N3	Mean
DN P1	6990	7135	6677	6934	6828	7403	6365	6865
DN P2	6334	6678	6809	6607	6336	6780	7269	6795
DW P1	7501	7857	8143	7834	8380	8463	8868	8570
DW P2	6709	7522	8040	7396	8446	8589	8886	8640
DN	6662	6907	6743	6771	6582	7092	6817	6830
DW	7105	7690	7350	7615	8413	8526	8877	8605
P1	7246	7496	7410	7384	7604	7933	7617	7718
P2	6522	7100	7383	7001	7391	7685	8078	7718
Mean	6884	7298	7396		7498	7809	7847	

Table 11. Yield component analysis for Experiments 1 and 2, Coimbatore, India (cv. IR50). DW = with drainage, DN = without drainage, P1 = 67 hills m^{-2}, P2 = 80 hills m^{-2}, N1 = 100 kg N ha^{-1}, N2 = 150 kg N ha^{-1}, N3 = 200 kg N ha^{-1}.

Treatments	Experiment 1						Experiment 2					
		Spikelets/panicle (No.)						Spikelets/panicle (No.)				
	Prod. tillers	Total	Filled	Unfilled	1000 g. weight	Harvest index	Prod. tillers	Total	Filled	Unfilled	1000 g weight	Harvest index
	Drainage											
DN	10.16	73.5	50.8	22.7	18.28	0.48	10.14	79.5	56.9	22.7	18.65	0.498
DW	9.71	73.3	59.8	13.5	18.48	0.515	10.17	78.9	65.7	13.2	18.87	0.556
SE_d	0.31	1.4	1	0.7	0.24	0.012	0.33	0.9	0.7	0.6	0.23	0.017
CD (P = 0.05)	NS	NS	2.2	1.6	NS	0.027	NS	NS	1.6	1.2	NS	0.039
	Density hills m^{-2}											
P1	10.71	76.3	57.2	19.1	18.36	0.501	11.1	80.5	62	18.7	18.47	0.547
P2	9.17	70.5	53.4	17.1	18.4	0.493	9.21	71.9	60.1	17.3	19.05	0.517
SE_d	0.31	1.4	1	0.7	0.24	0.012	0.33	0.9	0.7	0.6	0.23	0.017
CD (P = 0.05)	0.7	3.1	2.2	1.6	NS	NS	0.75	2.1	1.6	NS	NS	NS
	Nitrogen kg ha^{-1}											
N1	9.77	71.6	55.1	16.5	18.21	0.502	9.69	76.7	61.3	15.4	18.46	0.539
N2	10.07	73.6	55.6	18	18.42	0.499	10.25	79.1	61.3	17.2	18.83	0.529
N3	9.98	75.1	55.2	19.9	18.51	0.49	10.38	81.8	60.5	20.6	18.98	0.513
SE_d	0.28	1.4	1.3	0.7	0.14	0.012	0.26	1.1	0.6	0.7	0.16	0.01
CD (P = 0.05)	NS	2.8	NS	1.4	0.28	NS	0.54	2.3	NS	1.5	0.32	0.021

NS = Not significant
SE_d = Standard error of difference
CD (P=0.05) = Critical difference

Conclusions

Providing drainage was very effective in increasing grain yield in the experiments reported here. The importance of drainage was illustrated by the differences in root length, weight, diameter and activity between drained and undrained plots. Higher yields could be explained by a higher grain filling percentage under drained soil conditions. The number of productive tillers per unit area and 1000 grain weight were not much affected by the various treatments. Enhancing N application rate had a mixed effect on grain yield. The response to higher N input levels was conspicuous up to 150 kg/ha. Increasing N application rate to 200 kg N/ha decreased grain yield if no drainage was provided. Higher N application rates had a significantly favourable effect on leaf production in the beginning of the growth but effect was not reflected in final yield. Senescence of leaves was delayed by better drainage conditions. Drainage plots showed a better remobilization of stem reserves than undrained plots. Nitrogen content of plant organs was strongly affected by drainage and N application rate. The nitrogen content of dead leaves increased towards maturity. Drainage induced a better translocation of stored N from the stem. In general N uptake continued till maturity. It was steady and continuous and higher under drained soil conditions. Beneficial effects of drainage on root length, weight and activity were not visible in the early stages of crop growth, but became very clear after panicle initiation.

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The characteristics of N uptake and its effect on yield formation of hybrid rice with different growth durations

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Abstract

The characteristics of N uptake of two F1 lines of hybrid rice with different growth durations were studied. The total N uptake of the long growth duration line Sanyou 63 was greater than that of the short growth duration line V64. The increased amount of N in Sanyou 63 was attributed to its longer nursery period. The N uptake rate per unit root mass was greater in V64 than in Sanyou 63. In the field, V64 absorbed more N during the early stage but less during the middle stage compared with Sanyou 63. There was a close correlation between yield, yield components and the amount of N uptake. Techniques of fertilization and optimum growth duration are also discussed in this paper.

Introduction

With the introduction of hybrid rice breeding in China, grain yields have increased rapidly. Before 1981, most of the F1 lines were of the large panicle type with a long growth duration (130 - 140 days) (Yuan, 1988). In southern China, the relatively short growing season is a limiting factor for planting two hybrid rice crops with a long growth duration. Therefore, more and more F1 lines with short growth duration (110 days) have been produced by breeders in recent years. Yield formation characteristics vary among the F1 lines with different growth durations (Guo, 1991). Generally, the grain yield of short growth duration varieties is lower than that of long growth duration ones (Vergara, 1966, Cruz, 1987). This is because short growth duration varieties do not have a long enough growth period to produce a large number of panicles and sufficient leaf area (Vergara, 1964). Yokoo and Okuno, (1981) suggested that low yield of short duration varieties is related to the small sink size. Both sink size and grain yield, however, are also affected by the amount of N uptake (Akita, 1987, Shi, 1989, 1993).What is the effect of N on yield formation of hybrid rice with different growth durations? To answer this question, we chose two popular F1 lines with different growth durations to study the characteristics of N uptake and the relation between N uptake and yield formation at different N levels. Results of this study are reported in this paper.

Materials and methods

The experiment was conducted at Jiangxi Agricultural University, Nanchang, China in 1989. Two F1 lines were evaluated: V64 (short growth duration, 108d) and Sanyou 63 (long growth duration, 132d). Seeds were sown on 1 July for V64 and on 13 June for Sanyou 63. Both lines were transplanted on 24 July. Plant spacing was 13.3 cm × 20 cm.

The soil at the experimental plot was of clay loam texture, containing 3.78% organic matter, 0.12% total N, 81.2 ppm available N, 48.4 ppm available P, 77.4 ppm available K. The pH was 5.9. Nitrogen was applied at rates of 0, 75 , 150, 225 and 300 kg/ha in the form of urea. Half the dose was applied at transplanting and was trampled into the soil. The other half was given by surface broadcast at 7 days after transplanting (DAT) and 35 DAT respectively. Fertilizer treatments were tested for each line in three replications in 3.4 m × 4 m subplots.

In every subplot, five hills were sampled at transplanting, panicle initiation (PI), heading and harvest. The plant material was separated into leaves, stems and roots, and leaf area, dry weight of plant organs and final yield were measured. A yield component analysis was also conducted. The nitrogen content was analyzed by the Kjeldahl method.

Results

The characteristics of N uptake

Total amount of N uptake

The total amount of N uptake increased with increasing N application in both F1 lines (Table 1). Sanyou 63 absorbed 10.6% more N than V64, due to a better uptake during the nursery stage. The N uptake in the field was almost the same for the two F1 lines. The higher N uptake of Sanyou 63 during the nursery stage was related to its longer growth time in the nursery. In this experiment the nursery stage was 23 days for V64 and 41 days for Sanyou 63, respectively.

Although no differences were found in total field N uptake between both F1 lines, there were significant differences in uptake pattern (Table 1). In the early and late stages the absolute amount of N uptake and the percentage of the amount to the total field uptake were higher in V64 than in Sanyou 63. During the middle stage, however, the N uptake of Sanyou 63 was greater than that of V64.

N content in the plant at different growth stages

The N content in the plant was highest during the early stage for the two F1 lines (Table 2) and decreased with crop age. High amounts of N applicaion increased the N content in plant. The N content of leaves was higher than that of stems and roots. The N contents of leaves, stems and roots were all higher in V64 than those in Sanyou 63 over the entire growth period, but the differences were most evident during the early stage.

Table 1. The amount of N uptake in two hybrid rice lines with different growth duration, late season 1989, Nanchang, Jiangxi Province.

F1	Treatment	The amount of N uptake in field (kg/ha)							The amount of N uptake in nursery		Total amount of N uptake
Line	N (kg/ha)	Early stage	%	Middle stage	%	Late stage	%	Tot. upt. in field	Amount	Percentage	
		(0-21 DAT)		(22-61 DAT)		(62 DAT-harvest)			(kg/ha)	in total (%)	(kg/ha)
V64	0	20.9		37.6		31.5		90			98.5
	75	33.3		52.9		29.2		115.4			123.5
	150	42.7		73.8		34.4		150.9			159.4
	225	67.2		80.8		27.5		175.6			184.1
	300	59		102.2		34.5		195.7			204.2
	Ave.	44.6	30.6	69.5	47.8	31.4	21.6	145.5	8.5	5.5	154
Sanyou 63	0	8.4		57.9		38.1		104.4			129.2
	75	25.1		64.1		36.4		125.6			150.4
	150	37.6		84.9		19.1		141.6			166.4
	225	60.2		105.7		5.4		171.3			196.1
	300	55.5		114.6		14.9		185			209.8
	Ave.	37.4	25.7	85.4	58.7	22.8	15.6	145.6	24.8	14.6	170.4

Harvest time: V64, 89 DAT; Sanyou 63, 95 DAT

Table 2. N content (%) in various plant organs at different growth stages. Rice hybrid lines, late season 1989, Nanchang, Jiangxi Province.

	Treatment	Early stage			Middle stage			Late stage		
F1	N (kg/ha)	(0-21DAT)			(22-61DAT)			(62DAT-harvest)		
Line		Leaf	Stem	Root	Leaf	Stem	Root	Leaf	Stem	Root
V64	0	4.05	1.926	1.621	2.775	0.867	0.649	1.662	0.583	0.496
	75	4.188	2.1	1.901	2.884	1.071	0.96	1.784	0.638	0.518
	150	4.376	2.251	1.979	3.199	1.296	1.199	1.962	0.746	0.698
	225	4.688	2.307	2.101	3.622	1.537	1.46	2.221	1.022	0.967
	300	4.679	2.402	2.29	3.892	1.741	1.669	2.613	1.222	1.21
	Ave.	4.396	2.197	1.978	3.274	1.302	1.187	2.048	0.842	0.778
Sanyou 63	0	3.468	1.492	1.361	2.588	0.887	0.759	1.655	0.592	0.579
	75	3.597	1.581	1.461	2.781	0.989	0.97	1.794	0.604	0.61
	150	3.775	1.716	1.619	3.009	1.162	1.153	1.891	0.664	0.671
	225	4.072	1.903	1.813	3.49	1.448	1.511	2.225	0.844	0.856
	300	4.125	1.931	1.895	3.576	1.547	1.49	2.491	0.988	0.977
	Ave.	3.807	1.725	1.63	3.089	1.207	1.177	2.011	0.738	0.739

N uptake rate per unit root mass

The average nitrogen uptake per unit root mass is expressed as Nc/Mr (ten Berge et al., 1994). Nc (kg/ha) is the total amount of N absorbed during a certain stage. Mr (kg/ha) is the average root weight assessed from sampling at the beginning and the end of this period. The average N uptake per unit root mass increased with higher N application levels in the early and middle stages. V64 had a greater average uptake rate per unit root mass than Sanyou 63 (Table 3). At the early stage V64 had a higher uptake rate per unit root mass than Sanyou 63 at all of the N levels. But at the middle stage V64 had higher uptake rate per unit root mass only above the level of 150 kg N. Although the uptake rate decreased rapidly during the late stage, V64 still had a higher N uptake rate per unit root mass than Sanyou 63.

The relationship between N uptake and yield formation

The effect of N application on yield

Sanyou 63 had higher yield than V64 at N application levels of 0, 75 and 150 kg/ha (Figure 1, Table 4). But above 150 kg/ha of N, the yield of Sanyou 63 was lower than V64. The highest yield obtained was at 150 kg N and 225 kg N by Sanyou 63 and V64, respectively. Figure 2 shows the close correlation between grain yield, Y, and N uptake, Nc. The regression equation is as follows:

$$Y = -1861.712 + 116.7224\,Nc - 0.3421061\,Nc^2 \qquad (r = 0.9019)$$

The calculated result shows that maximum yield would be obtained with an N uptake of 170 kg /ha.

The effects of N application on yield component

Grain yield is mainly determined by the number of panicles per unit area and the number of spikelets per panicle. In this experiment the panicle number increased with higher N application. Conversely, spikelet number per panicle decreased with the increased levels of N application (Table 4). V64 had more panicles but less spikelets per panicle than Sanyou 63.The path coefficient analysis (Dewey & Lu, 1959) showed that the direct effect of panicle number to yield in V64 was the most impotant. The path coefficient was 1.3567 for panicles number, 0.284 for spikelets number per panicle, 0.0165 for both 1000 grain weight and filled grain percentage. In Sanyou 63 1000 grain weight was the most important factor to yield determination. The path coefficient was 2.8603 for 1000grain weight, 2.0404 for filled grain percentage, 1.3994 for spikelets number per panicle and 0.2591 for panicle number.

Table 3. The average N uptake per unit root mass in different growth stages (Nc/Mr, kg/kg).

F1 Combination	Treatment N (kg/ha)	Early stage (0-21 DAT)	Middle stage (22-61 DAT)	Late stage (62 DAT-harvest)
V64	0	0.134	0.055	0.025
	75	0.168	0.057	0.018
	150	0.191	0.069	0.019
	225	0.238	0.073	0.015
	300	0.233	0.104	0.02
	Ave.	0.193	0.072	0.019
Sanyou 63	0	0.038	0.059	0.02
	75	0.093	0.056	0.017
	150	0.127	0.063	0.009
	225	0.173	0.071	0.002
	300	0.177	0.081	0.007
	Ave.	0.122	0.066	0.011

Table 4. The effects of different N levels on yield components and yield.

F1 Combination	Treatment N (kg/ha)	Plant height (cm)	Panicle number (m^2)	Spikelet number p.panicle	Spikelet number ($m^2 \times 103$)	Filled grain (%)	1000 grain wt (g)	Grain yield (kg/ha)
	0	80.4	289	90.6	26.1	82.6	29.7	6422
V64	75	81.1	343	86.9	29.8	80.6	30.5	7313
	150	85	386	88.7	34.2	77.2	29.8	7856
	225	80.2	436	80.8	35.2	78.4	28.9	8094
	300	80.8	458	77.1	35.3	78.3	28.4	7881
	Ave.	81.5	382	84.8	32.1	79.4	29.5	7513
Sanyou 63	0	92.6	226	127.1	28.8	88.2	28.6	7269
	75	95.8	251	135.5	34	84.4	28.3	8138
	150	95.8	276	124.6	34.4	84.9	28.2	8269
	225	95.8	305	108.6	33.1	84.7	27.9	7838
	300	94	316	105.4	33.3	82.3	26.7	7369
	Ave.	94.8	275	120.2	32.7	84.9	27.9	7776

Yield data was presented as rough rice at 14% moisture.

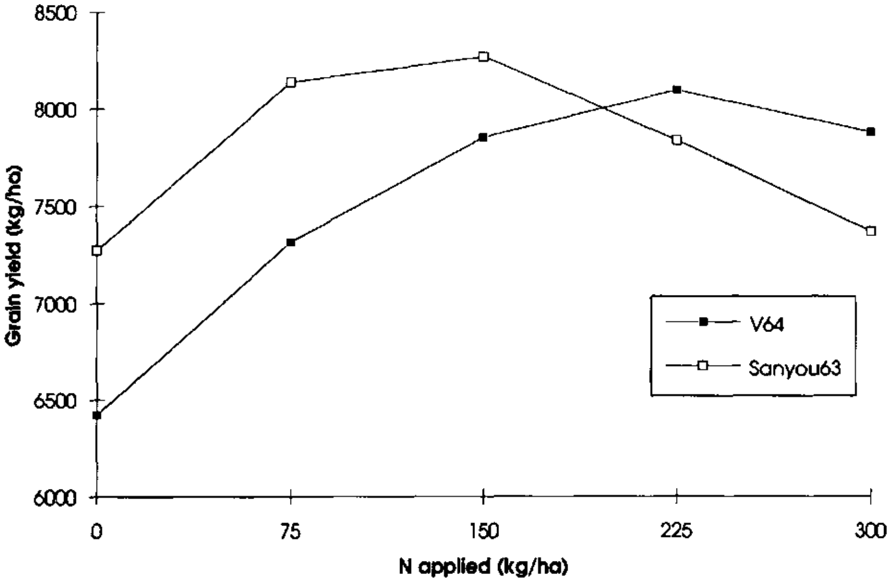

Figure 1. The effects of N application on grain yield in two hybrid lines. Late season, 1989, Nanchang, Jiangxi Province.

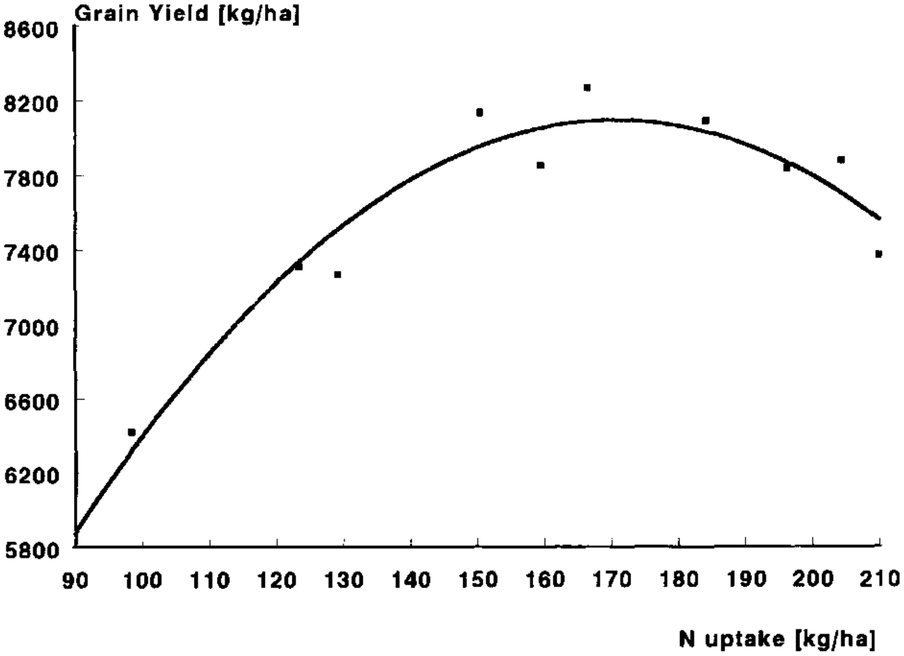

Figure 2. Relation between N uptake and grain yield in two hybrid lines. Late season, 1989, Nanchang, Jiangxi Province.

There was a close correlation between grain yield (Y) and panicle number (P) for the two F1 lines:

$$Y = -402.078 + 65.035\,P - 1.312\,P^2 \qquad (r = 0.9884, \text{V64})$$
$$Y = -1901.229 + 270.692\,P - 7.468\,P^2 \qquad (r = 0.9987, \text{Sanyou 63})$$

The equations show that the highest yield was achieved when the panicle number was at 431 m^{-2} and 272 m^{-2} for V64 and Sanyou 63 respectively.

The effect of N application on LAI

The LAI of Sanyou 63 was higher than that of V64 at different N levels (Table 5). The LAI increased with the increased levels of N application for both F1 lines. LAI was highest at the N level of 225 kg/ha, and decreased above that level. Figure 3 showed that there was a good correlation between grain yield and LAI. The equation is as follows:

$$Y = 2611.35 + 1157.19\,LAI - 61.56\,LAI^2 \qquad (r = 0.91)$$

The optimum LAI calculated was 9.4 for both lines.

The effects of N application on biomass

The biomass of roots and shoots in both lines was increased with increasing N application, but decreased when N application was above 225 kg/ha (Table 6). The decreased biomass at high N levels might be related to high respiration losses (Shi and Akita, 1988). The pattern of biomass production over different stages closely followed that of total N uptake. The net increase of biomass was higher in V64 than in Sanyou 63 during the early and late stages, but during the late stage it was higher in Sanyou 63, as reflected in N uptake.

Table 5. Leaf area index of two rice hybrid lines. Late season 1989, Nanchang, Jiangxi Pr.

F1 Combination	Treatment N (kg/ha)	PI (21 DAT)	Heading (61 DAT)
V64	0	1.88	4.25
	75	2.56	6.61
	150	2.93	8.38
	225	3.83	10.4
	300	3.33	9.77
Sanyou 63	0	2.45	5.59
	75	3.38	7.79
	150	3.89	10.75
	225	4.73	11.82
	300	4.75	11.52

PI: Panicle Initiation

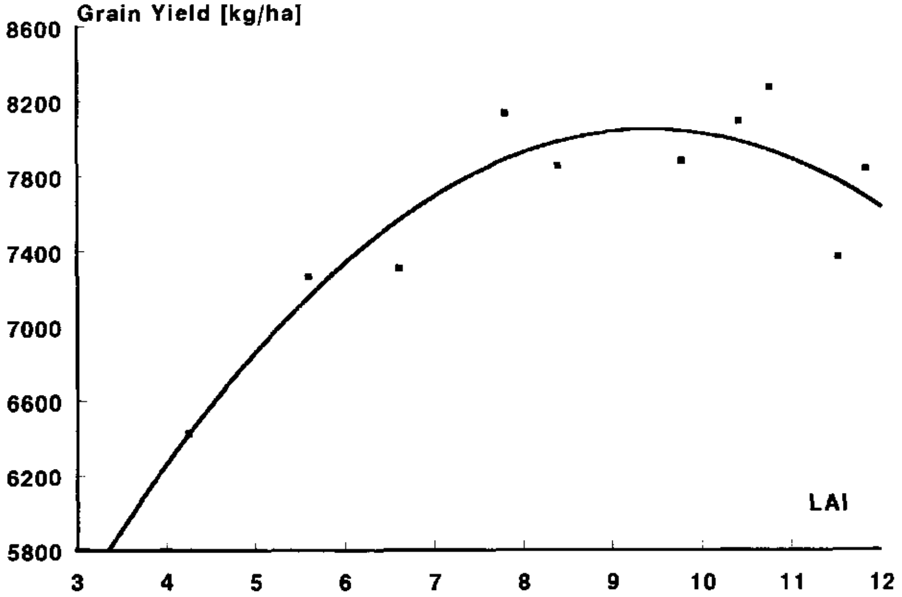

Figure 3. Relation between LAI and grain yield in two hybrid lines. Late season, 1989, Nanchang, Jiangxi Province.

Table 6. Biomass of roots and shoots (kg/ha) in two hybrid lines, late season, 1989, Nanchang, Jiangxi Province.

F1 Combination	Treatment N	21 DAT		61 DAT		Harvest	
	(kg/ha)	Roots	Shoots	Roots	Shoots	Roots	Shoots
V64	0	282	1310	1098	5490	1401	9328
	75	365	1519	1488	6761	1675	11169
	150	416	1571	1736	7232	1872	12474
	225	533	2009	1676	7288	1991	13274
	300	475	1740	1493	6691	1925	12833
	Ave.	414	1630	1498	6692	1773	11816
Sanyou 63	0	302	1485	1673	7272	2119	12466
	75	413	1964	1883	8554	2343	13781
	150	461	2098	2255	9394	2233	13958
	225	566	2357	2415	10061	2130	14201
	300	498	2167	2321	9675	2091	13944
	Ave.	448	2014	2019	8991	2183	13670

Discussion

In this experiment the total N uptake of the long growth duration line Sanyou 63 was greater than that of the short growth duration line V64. The difference was due to its longer nursery period (Table 1). In southern China, the varieties with long total growth duration usually have a long nursery duration too, because the field season is confined. Therefore, nursery management is important, especially for those varieties that spend more than one fourth of their total cycle duration in the nursery.

Most of the 'panicle weight' type varieties have a longer growth duration than the 'panicle number' type varieties. Sanyou 63 is of the panicle weight type, V64 is of the panicle number type (Guo, 1991). The average N uptake per unit root mass in Sanyou 63 was lower than that in V64. But the total amount of N uptake in the field was similar for the two lines because Sanyou 63 produced more roots (Table 6). The varieties of panicle number type absorb more surface N in soil because of their shallow rooting. The varieties of panicle weight type, in contrast, are able to better utilize subsoil N (Kawata, 1982). Hen and Liu (1989) also suggested that Sanyou 63 absorbed more N from the subsoil. Although the N application levels were different for the optimum grain yield between the two F1 lines, there was a close correlation between yield and N uptake.

The N uptake rate per unit root mass and the uptake amount were larger in the early stage in V64 than in Sanyou 63 (Tables 1, 3). Cruz (1987) reported that a relationship exists between N absorption ability and tiller number before the maximum tillering stage. V64 had fewer spikelets per panicle than Sanyou 63. A higher panicle number can compensate for a lower number of spikelets per panicle. Therefore the effect of early N uptake on yield formation was more important in V64 than in Sanyou 63. In the middle stage the absolute amount of N uptake in V64 was much smaller than in Sanyou 63 although the N uptake rate per unit root mass in V64 was still somewhat higher. The growth of root and shoot biomass in the middle stage was larger in Sanyou 63, which might be related with the formation of the large panicles. In the late stage, N uptake at the low N level was more in Sanyou 63 than V64, but was less with the increase of N level. This indicates that the N uptake in the late stage mainly depended - in Sanyou 63 - on the amount of N taken up during the early and middle stages. V64 was less sensitive to the higher N level. As mentioned above, N application for the short duration F1 line V64 should be concentrated on the early stages to promote tillering. For the long duration line Sanyou 63, part of the N should be applied at the beginning of the middle stage to promote the formation of large panicles.

In recent years the optimum growth duration has been shortened with increased N application. At low N levels, the optimum growth duration was 140 days (Vergara, 1966). It was shortened to 120 days at middle N levels (Kawano and Tanaka, 1968) and then shifted to 100-110 days at very high N levels (Akita, 1987). In this experiment the growth duration of V64 was 24 days shorter than that of Sanyou 63, but yields were similar. This demonstrates that in the southern part of China, the short duration F1 lines could obtain similar yield as the long duration ones, provided that N uptake is increased.

Conclusions

The short growth duration V64 had a greater N absorption ability in the early stage; this enhances the production of tillers and helps to quickly establish a large leaf area index. The high yield of a short duration line under high N levels was associated with a limited vegetative growth period, which prevents the excessive production of vegetative biomass. The long duration line sanyou 63 had higher yield than V64 at low N levels, which was associated with a well developed root system and longer vegetative growth period. Higher N levels did increase N uptake and yield in Sanyou 63, but if the uptake amount exceeded an optimum value, the yield decreased. Large N uptake resulted in very high LAI, which is supposed to enhance carbohydrate losses via dark respiration (Shi and Akita, 1993).

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Soil hydraulic properties database for crop growth simulation models

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Abstract
The water retention characteristics of soils are an important input for crop growth models used under water limited conditions but are difficult to measure. Regression analysis was used to relate these characteristics to more easily measurable soil properties, i.e. bulk density, organic carbon content, and percentages silt, clay and sand. Such properties are often routinely determined during soil surveys. Focus was on four 'critical' water contents: saturated water content, water content at field capacity (soil pressure potential h = -10 kPa), water content at wilting point (h = -1.5 MPa) and water content at air dryness (h = -31 MPa). The data used represented soils of alluvial, black, laterite and lateritic, red, and desert regions of India. Soil water content at saturation and field capacity were negatively correlated and satisfactorily estimated using sand content. Water content at wilting point was positively correlated with and satisfactorily estimated from clay content. The difference in r^2 using all variables together or the best variable only was very small (about 2%). Hygroscopic coefficient values were assumed to represent the air dry water content and could be estimated accurately from clay content.

Introduction

The Rice-wheat cropping system is prevalent in the Indo-gangetic plains of the Indian subcontinent where both crops grow under a diverse set of climatic conditions as well as on soils differing markedly in their hydrophysical properties. Crop growth simulation models may allow a more quantitative understanding of the system. For rainfed conditions, a realistic soil water balance is an integral component of such models. Soil-water balance modules can be categorized into capacity and mechanistic models. Capacity models describe water transport in soils partly by integrating (over time and/or depth) calculations rather than solving the general flow equation, which combines Darcy's law and an expression for conservation of mass. Mechanistic models are usually defined as models that describe water distribution in soils by solving the general flow equation (usually numerically). Capacity models are simpler than mechanistic models and require less input data. Mechanistic models are generally preferable if the soil-water system does not reach an equilibrium state within the period of one time step of the main (crop growth) simulation model (Bouma et al., 1993). An example of a capacity model is SAHEL (Penning de Vries et al., 1989). In SAHEL, the root zone is seen as a 'box' which contains water within two predefined critical pressure heads: 'field capacity' and 'wilting point'. When water is applied to the soil, it is assumed to be rapidly redistributed when the water content is above field capacity. The excess water flows downward. Water can be extracted to the wilting point, water held at lower pressure heads is unavailable for plants. In capacity type models like SAHEL, instead of the complete soil water retention curve $h(\theta)$, which relates soil water pressure potential h to soil water content θ, input is confined to four constants only. These are the soil water contents at saturation (θ_{sat}), field capacity (θ_{fc}), wilting point (θ_{wp}) and air dryness (θ_{ad}). θ_{sat} represents the total porosity of soil or water held by soil at $h = 0.0$ MPa. θ_{fc} is the water held by the soil at $h = -0.01$ MPa and is considered as the upper limit of available water for crops other than rice. θ_{wp} is the water held by the soil at $h = -1.50$ MPa and is often assumed to be the lower limit for crop-available water. θ_{ad} is the lower limit of soil water content. In this study it was set to the soil water content corresponding to the hygroscopic coefficient value ($h = -31.0$ MPa).

Direct data on soil water content values at saturation, field capacity, wilting point and air dryness are often not available. Attempts have, therefore, been made by many researchers (e.g. Clapp and Hornberger, 1978; Gupta and Larson, 1979; Rawls and Brakensiek, 1982; and Vereecken et al., 1990) to derive soil water retention characteristics from other soil properties, like soil texture, organic carbon content and occasionally bulk density values. Such data are often routinely determined during soil surveys. In this study, regression analysis was used to relate soil water contents at saturation, field capacity, wilting point and air dryness to more easily measured soil properties.

Materials and methods

Two complete datasets, presented by Ali et al. (1966) and Gupta et al. (1984) were used as a database. These datasets provide information on soil water retention characteristics and other soil properties (percentages sand, silt, clay, organic carbon and bulk density) for soils of alluvial, black, laterite and lateritic, red and desert regions of India. Data ranges in the database are summarized in Table 1.

Regression analysis was used to determine correlation coefficients between soil properties and to develop regression relationships using simple, multiple and step-wise regression techniques. Percentages of silt, sand, clay and organic carbon and bulk density were defined as the independent variables, while θ_{sat}, θ_{fc}, θ_{wp} and θ_{ad} were the dependent variables.

Measured and estimated values for the four critical soil water contents of 10 soils from the database were used as an input for the wheat growth model WTGROWS (Aggarwal et al., 1994), using 5 years of actual weather data from New Delhi. Simulated yields for measured and estimated input were compared. This approach will only give a first impression of the effectiveness of the regression models. Future work will involve an independent check by predicting the four critical soil water contents for new soils, that have not yet been incorporated in the database.

Table 1. Summary of soil properties used in the database (total number of datasets: 106).

Variables	Mean	Minimum	Maximum
Sand (%)	54.4	0.3	97.0
Silt (%)	16.1	0.4	42.3
Clay (%)	29.5	2.2	79.8
Organic carbon (%)	0.6	0.02	3.08
Bulk density (g/cm^3)	1.46	1.13	1.81
θ_{sat} (cm^3 cm^{-3}) [1]	0.56	0.29	3.08
θ_{fc} (cm^3 cm^{-3})	0.45	0.1	0.91
θ_{wp} (cm^3 cm^{-3})	0.14	0.02	0.35
θ_{ad} (cm^3 cm^{-3}) [2]	0.09	0.01	0.24

1 Based on a subset of 98 observations

2 Based on a subset of 75 observations

Results and discussion

Correlation Coefficients

As a first step, the correlation coefficients between all variables were calculated. All variables were significantly correlated (Table 2). The dependence of soil water retention characteristics on the soil physical and related properties has been reported by many workers (e.g. Ali et al., 1966; Biswas and Ali, 1967; Velayutham and Raj, 1971; Gupta and Larson, 1979).

Regression Analyses

Multiple and step wise regression analyses were carried out with θ_{sat}, θ_{fc}, θ_{wp} and θ_{ad} as dependent variables and the remaining as independent variables. When all five independent variables were taken together the r^2 ranged from 70 to 87% (significant at P=0.01 level). Using step wise regression analysis, the number of independent variables could be reduced from five to only one without sacrificing much on r^2, i.e. about 2%.

Table 2. Correlation coefficients r between soil properties in the soil database.

	Sand	Silt	Clay	Org. C	Blk dens.	θ_{sat}	θ_{fc}	θ_{wp}
Sand	1							
Silt	-0.7572	1						
Clay	-0.9377	0.4841	1					
Org. C	-0.4328	0.3504	0.3959	1				
Blk dens.	0.5341	-0.3956	-0.5125	-0.5017	1			
θ_{sat}	-0.8243	0.5603	0.8205	0.3739	-0.4265	1		
θ_{fc}	-0.8951	0.6335	0.8605	0.3816	-0.348	0.888	1	
θ_{ad}	-0.8707	0.4554	0.9228	0.3457	-0.4083	0.8616	0.8867	1

The following four simple regression models were derived for estimating the four critical soil water contents:

$$\theta_{sat} = 0.8195 - 0.0046 * \text{Sand}\,(\%) \quad r^2 = 0.68 \quad ...... \qquad (1)$$

$$\theta_{fc} = 0.7919 - 0.0063 * \text{Sand}\,(\%) \quad r^2 = 0.80 \quad ...... \qquad (2)$$

$$\theta_{wp} = 0.0137 + 0.0043 * \text{Clay}\,(\%) \quad r^2 = 0.85 \quad ...... \qquad (3)$$

$$\theta_{ad} = -0.0178 + 0.6556 * \theta_{wp} \quad r^2 = 0.90 \quad ...... \qquad (4)$$

Equations (1) - (4) were used to predict the four critical soil water contents for ten soils selected from the data base. The main selection criterion was to choose soils having a wide range in sand, silt, clay and organic carbon contents. The magnitude of these properties for the selected soils ranged from 0.5% to 89% for percentage of sand, 4.1% to 39% for percentage of silt, 5% to 79.8% for percentage of clay, and 0.18% to 1.76% for organic carbon content. The values predicted by Equations (1) to (4) and the corresponding observed values are shown in Figure 1. The r^2 value was 0.93, indicating a close agreement between the observed and predicted values. The selected soils were part of the database that was used to derive the regression models. Future work will involve independent testing of the models using soil data not yet incorporated in the database.

Simulations conducted using five years of Delhi weather data showed that both yield and evapotranspiration were unaffected if estimated rather than measured values for the critical soil water contents were used.

Results presented here are encouraging as they show the possibility to use regression models to derive important soil water retention characteristics from relatively easily measurable soil properties. If possible, such methods should always be checked, however, by actual measurements.

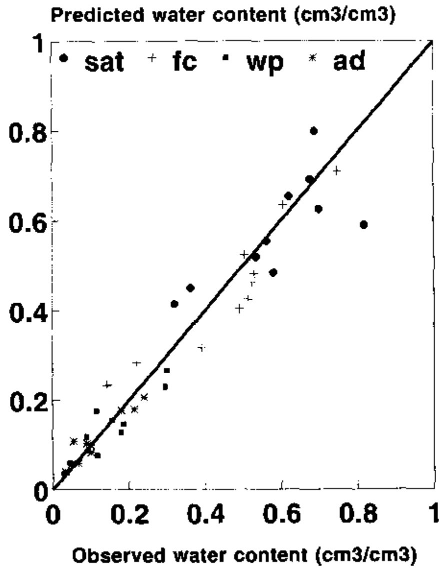

Figure 1. Observed and predicted values of four critical soil water contents θ_{sat}, θ_{fc}, θ_{wp} and θ_{ad} for 10 selected soils from the database using regression models (1) - (4).

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A new model of nitrogen allocation and synthesis of dry matter in crops, applied to rice

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Introduction

Emphasis on the efficiency of crop productivity has progressively become the prime consideration in agricultural research, especially during the last decade. This is associated with the restriction in the expansion of arable lands while population growth continues. This is particularly evident for rice production. A global perspective study, commissioned by the Food and Agriculture Organization of the United Nations, predicts that the world demand for rice will increase at the annual rate of 2.5% from 1980 to 2000. The increase must come largely from the increases in rice production per unit area (Seshu et al., 1989).

The efficiency of rice production, as of the other crops, is basically determined by the ability of the crop to intercept and convert solar energy into chemical compounds which are essential for growth. Operations of such basic processes, for a given variety, are affected by the other environmental variables. It is well established that not only light use efficiency, but also the expansion of growing tissue of a species is considerably determined by crop nitrogen (N) content (eg. Sinclair and Horie, 1989; Moorby and Besford, 1983; Mengel and Kirkby, 1978). Under field (especially rainfed) conditions, productivity of rice is often constrained by the limited supply of N. Research has been continually conducted to investigate factors and processes affecting N availability in the soil, its distribution within the crop, and its effects on growth and yield (IRRI, 1979). The findings have led to significant improvement in crop management and productivity. However, it was observed that rice yield variability increases as nitrogen fertilizer rates increase (Evans and De Datta, 1979). This is caused by the greater responses of the crop which has received higher N doses to the other fluctuating environmental factors (De Datta, 1981). Because the conditions under which rice is grown are extremely variable, especially the rainfall which varies in both space and time (Fukui, 1982), high rates of N application do not always ensure proportional increases in yield. Due to complex crop-environment interactions, together with economic considerations and environmental concerns, a detailed strategy and systematic approach to crop production and fertilizer management are needed in order to achieve a greater efficiency of crop production, while maintaining sustainability of the system and the environment.

Simulation of crop growth is a tool that can be applied to study cause-effect relationships in such a complex systems, and to investigate the technical possibilities and scenarios to achieve the defined objectives. Applications of simulation models for the improvement in rice productivity are exemplified by e.g. the design of alternative plant types (Dingkuhn et al., 1992; Penning de Vries, 1991), and the analysis of rice ecosystem and yield constraints in order to improve crop management (Kropff et al., 1992; van Keulen, 1977).

As empirical relations in a model are gradually replaced by quantified mechanistic representations of processes, the suitability of the model to analyze system behaviour and the interactions with the external driving variables increases. Therefore an attempt is made in the present work to extend the existing mechanistic rice growth models by describing growth as a function of N uptake, glucose and N allocation, and growth efficiency of individual organs in relation to their biochemical constituents. This approach differs from that in most current crop growth simulation models, where the demand for and distribution of N are defined on the basis of total existing dry matter of leaves, stems, etc. Such models do not allow the description, on the basis of the relative availabilities of C and N, of growth respiration and dry matter formation, and the formation of shielded reserves (starch). The model NASYM (Nitrogen Allocation and Synthesis of dry Matter) which we propose here simulates these processes on the basis of underlying mechanisms. Moreover, the approach reduces the number of crop specific inputs. Maximum and minimum N contents of tissues are no longer a function of development stage since they refer to new biomass and not to bulk existing crop biomass. The model as presented here still uses nitrogen uptake and dry matter partitioning as forcing functions and avoids the formulation of nitrogen demand. We believe, however, that the model provides a sound starting point for developing additional simulation routines describing nitrogen demand and dry matter allocation among organs, based on momentary availabilities of carbon and nitrogen in the crop.

The algorithm of the NASYM model is written in FORTRAN-FSE in a modular form. The codes of the main model and all subroutines are given in Pannangpetch and ten Berge (1994), along with all input files and with a more elaborate validation than can be given here.

Model description

N requirement

Growth can be regarded as the result of synthesis of new dry matter which can comprise both the formation of new tissue, and the expansion/enrichment of the previously formed tissue. N is required for the synthesis of nitrogenous compounds, especially proteins, which are essential for the growth process. N requirement (Nq, kg N ha^{-1} d^{-1}), for synthesis of new dry matter during an interval of time may be described as:

$$Nq = G * FN \tag{1}$$

where G is new dry matter produced (kg ha^{-1} d^{-1}), and FN is the fraction of N in new dry matter (kg N kg^{-1} $_{DM}$). If other factors are not limiting, the synthesis of new dry matter is determined by the rate at which carbohydrates become available (Cv, kg glucose ha^{-1} d^{-1}) and by the growth efficiency. Growth efficiency is defined as dry matter synthesized per unit of glucose allocated (GE, kg DM kg^{-1} $_{glucose}$). The N requirement thus becomes

$$Nq = Cv * GE * FN \tag{2}$$

Growth efficiency of an organ is basically determined by its biochemical composition. A tissue containing a higher fraction of protein has a lower growth conversion coefficient. This is due to the relatively high cost of protein synthesis. The average value for synthesizing a kg of protein is 1.887 kg of glucose (Penning de Vries et al., 1989). Because a large proportion of N in a tissue is incorporated in the form of protein, the growth efficiency of a tissue is a function of its N fraction. Thus, the N requirement of an organ for synthesis of new dry matter over a time interval is a function of the carbohydrate allocation to that organ and the corresponding fraction of N in the new dry matter being synthesized during that interval of time.

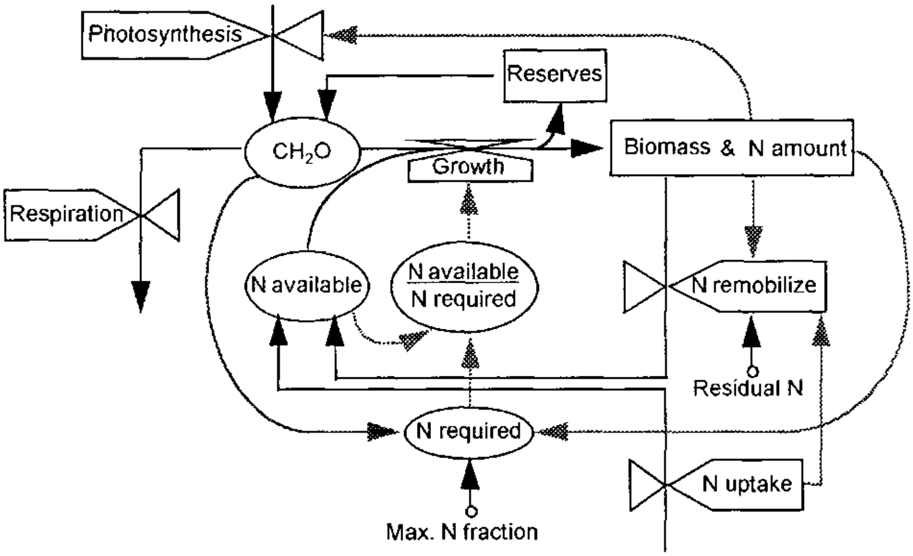


Figure 1. Relational diagram of the NASYM model.

The fraction of N in new dry matter (*FN*) varies with development stage, and the relative availabilities of N and carbohydrates. The possible range of *FN* is from 0.0 to 0.15. If all new dry matter comprises only proteins, eg. when only the protein content of the previously formed tissue is increased, the maximum attainable *FN* is 0.15, the average fraction of N in proteins (Penning de Vries et al., 1989). On the other hand, if new dry matter consists of only carbohydrates and polysaccharides, then the fraction is 0.0. The value of 0.15 may be regarded as the maximum theoretical value. A similar value of N content in protein, 16%, was also found in *Zea Mays* (Epstein, 1972). During the process of growth, synthesis of the components other than proteins is concurrently operating. Thus, when N is not limiting, these processes may compete for carbon and the maximum attainable *FN* may be lower than the theoretical value. Different species exhibit differences in the competition for carbon among these synthetic processes. Generally, C3 plants have a tendency to have higher protein levels in leaves than C4 plants. In C3 leaves, ribulose 1,5-biphosphate carboxylase alone accounts for up to 50% of the soluble protein, while in C4 leaves it accounts for only 10-25% of the soluble protein (Schmitt and Edwards, 1981).

If we accept the hypothesis that the newly formed tissues of emerging seedlings contain the highest attainable protein and N contents ever found, the value of maximum attainable fraction of N in new dry matter formed during any stage of crop growth (*FNmax*) can be derived for rice directly from the growth efficiency during seed germination and early growth in the dark, during which starch and nitrogenous compounds available from the seed provide all glucose and nutrients for growth. Protein synthesis is a major biological process occurring in both the embryonic axis and the cotyledons of germinating seeds (Brooker et al., 1977), and a prerequisite for radicle emergence (Bewley and Black, 1978). Isolated embryos of rice and wheat commence protein synthesis within 30-40 min. of being introduced to water (Bewley and Black, 1978). It is generally accepted that protein synthesis is very high in germinating seeds and the above hypothesis seems to be warranted. Respiration of germinating is confined mainly to support the synthesis of new dry matter. Growth efficiency during this stage is 0.6 kg kg^{-1}; for each kg of the reserves in seed being used to form new dry matter, 0.6 kg of new dry matter is produced and 0.4 kg is respired to provide the energy for the synthetic conversion processes (Yoshida, 1981; Penning de Vries, 1972). Because the reserves in rice grain are largely made up of starch, it can be assumed that formation of 1 kg of new dry matter will require 1.66 kg of glucose. It can be calculated with the help of known compositions - and their production costs - of the main biochemical constituents in leaves and roots (Penning de Vries et al., 1989) that the N fraction of the newly formed dry matter corresponding to this conversion factor of 1/1.66 is 0.1 kg kg^{-1}. The value of 0.10 kg N $kg^{-1}{}_{DM}$ is therefore assigned for *FNmax*. (Details of the calculation of glucose requirement to produce a unit of dry matter with specified fraction of N is described in Pannangpetch and Ten Berge, 1994.)

The fraction of N in new dry matter (*FN*) should be distinguished from the current fraction of N in total dry matter of the previously formed tissue (total N/ total W, $\overline{FN}$) which is a function of the state of crop. The distinction between the two is necessary in order to describe the rate of N requirement for synthesis of new dry matter during the growth process.

The following two cases may illustrate the distinction between *FN* and $\overline{FN}$. Generally rice grain contains an N fraction ($\overline{FN}$) of 0.012. As germination proceeds, 0.4 fraction of carbohydrate reserves is respired to provide the energy required for the synthesis of new dry matter. While the rice seedling may continue to synthesize this new dry matter with an N fraction (*FN*) of 0.1, $\overline{FN}$ will increase, due to losses of carbon in respiration, and could approach 0.02 ($\overline{FN}$) during early stage of growth.

In case when N available for synthesis of new dry matter is sufficiently and solely supplied from an external source, *FN* can be calculated directly from the expression $(N_{(t+1)}-N_t)/(W_{(t+1)}-W_t)$, where N is the total amount of N in leaf dry matter and W is total leaf dry matter, both at time *t* and *t*+1 d. If, at time *t*, total leaf matter is 100 kg with $\overline{FN}$ of 0.02, and at time *t*+1 total leaf dry matter is 130 kg with $\overline{FN}$ of 0.0385, then *FN* is equal to (5-2)/(130-100). Fraction of N in new dry matter synthesized during the time interval of 1 d is 0.1.

However, the condition where N available for the synthesis of new dry matter is solely supplied from root uptake rarely occurs. Three weeks after germination, the first leaf begins to senesce (Yoshida, 1981) and thus remobilization and reallocation of N has already occurred. N available for the formation of new dry matter during this period and thereafter will comprise both remobilized N and N from root uptake. Therefore, to derive a maximum value of *FN* from observed N(t) and W(t) using the expression $(N_{(t+1)} - N_t)/(W_{(t+1)} - W_t)$ could result in underestimation, because $(N_{(t+1)} - N_t)$ represents only the amount of N uptake by roots during the time interval of 1. For this reason, the value of the parameter *FNmax* for the current model is derived only from growth efficiency during seed germination.

Irrespective of the fraction of N in new dry matter being synthesized, not all protein formed will be incorporated in newly formed tissue. Part of the protein synthesis may occur within the previously formed tissues and remain there for local expansion/enrichment. This can be clearly observed in the leaf canopy of rice. While the upper most leaf is emerging, at least two leaves lower are still undergoing elongation and growth (Yoshida, 1981). Furthermore, intensification of the green colour of leaves that have already completed their expansion was observed after a high rate application of N (Sivasamy, TNRRI; Wopereis, IRRI; personal communications).

The following example will illustrate the definition of new dry matter which is used for both the formation of new tissue and the expansion/enrichment of the previously formed tissue.

Suppose that the existing mass of leaf tissue is 100 kg with $\overline{FN}$ of 0.02, and that 30 kg of new dry matter is synthesized with *FN* of 0.1. Based on a fraction of N in protein of 0.15 kg N $kg^{-1}_{protein}$, the old leaf tissue with $\overline{FN} = 0.02$ consists of 13.33 kg protein and 86.67 kg non-protein, whereas the new dry matter consists of 20 kg protein and 10 kg non-protein. If, for example, protein is distributed equally among each unit of non-protein part regardless whether it is newly or previously formed, then 3.45 kg protein and 10 kg non-protein from new dry matter will be used to form new tissue, while 16.55 kg of protein will be kept by the old tissue for its own expansion/enrichment. As a result, the formation of new tissue is only 13.45 kg in which 3.45 kg is protein, and the weight of old tissue is increased, due to the expansion/enrichment, from 100 kg to 116.55 kg in which 29.88 kg is protein. If the maximum capacity of protein content per a unit of tissue is reached, no further protein synthesis for expansion/enrichment would occur in these tissues in the following days.

$\overline{FN}$ varies with time, type of organ, environmental conditions and crop management. In rice, $\overline{FN}$ generally increases and reaches the peak around the tillering stage after which it declines as the plant develops. This fraction is generally higher in leaves than in stems and roots. Higher fractions are observed in plants that received high rates of N fertilizer, especially under low light intensity. The highest fractions observed, as compiled by Penning de Vries et al. (1990), are 0.06 for leaves, and 0.04 for stems. Leaf photosynthesis is known to increase linearly with the leaf N fraction, at least up to the N fraction of 0.06. Therefore it is, presently, assumed that all N within leaves up to the fraction of 0.06 is in the form of proteins. Similar values of N content in leaves were found in rice variety IR64 which received 150 kg N ha^{-1} as mineral fertilizer (Schnier et al., 1990). These fractions imply that there is a maximum limit to the amount of protein associated with a unit of non-protein in tissue. The maximum limit of $\overline{FN}$ will be referred to as $\overline{FN}max$. Therefore, if the existing formed tissue already has the N fraction equal to its maximum limit ($\overline{FN}=\overline{FN}max$), there will be no further net protein retention in this tissues: the N requirement is completely fulfilled. As a consequence, all the protein being synthesized is confined to only the formation of new tissue. In such state, *FN* would be less than the maximum *FNmax* of 0.1, and, at most, only corresponds to $\overline{FN}max$. This maximum limit applies to both newly formed and existing tissue. Under this "N-saturated state" :

$$\overline{FN} = \overline{FN}max \tag{3}$$

and:

$$FN = \overline{FN} \tag{4}$$

We take $\overline{FN}$ as the base-value for *FN*. The difference ($FNmax-\overline{FN}$) can then be regarded as the potential range by which *FN* can be increased. The demand to increase - by an amount ΔFN - this N fraction in newly formed dry matter with respect to the base-value depends on the relative N states of the existing tissue, $(\overline{FN}max-\overline{FN})/\overline{FN}max$. ΔFN is defined as:

$$\Delta FN = \frac{(\overline{FN}max - \overline{FN})}{\overline{FN}max}(FNmax - \overline{FN}) \tag{5}$$

Thus,

$$FN = \Delta FN + \overline{FN} \tag{6}$$

The above principle (Equations 5, 6) is applied to calculate *FN* of plant organs under both "N-saturated" and "N-unsaturated" states.

Summarizing the above description, the fraction of N in new dry matter (*FN*) is a function of:

1 *FNmax*. The value derived for rice is 0.10 kg N $kg^{-1}{}_{DM}$.
2 $\overline{FN}max$. The value varies according to type of tissues and variety. The general values for leaves, stems, roots, and grains are 0.06, 0.04, 0.04, and 0.015 kg N $kg^{-1}{}_{DM}$, respectively (Penning de Vries et al., 1990).
3 $\overline{FN}$, the current status of the existing tissue (kg N $kg^{-1}{}_{DM}$).

(The subscript DM refers to dry matter.) When $\overline{FN}$ is equal to 0, the equation will yield *FN* equal to *FNmax*. Because $\overline{FN}max$ varies with type of organ, we assume that organs with higher $\overline{FN}max$ represent stronger sink strength, and has a higher rate of N acquisition. A relative time coefficient (*Tq)* is applied to describe such a differences among organs.

$$Tq_i = Kq * FMAX / \overline{FN}max_i \tag{7}$$

where *i* is type of organ, and *FMAX* is the highest value of $\overline{FN}max$ among leaves, stems, and roots. An arbitrary constant *Kq* with the value of 2 is introduced to reflect that only half of the tissue previously formed is capable of exerting the demand of N for expansion/enrichment. The calculation of FN_i is thus extended as follows:

$$FN_i = \frac{(\overline{FN}max_i - \overline{FN}_i)}{\overline{FN}max_i}\frac{(FNmax - \overline{FN}_i)}{Tq_i} + \overline{FN}_i \tag{8}$$

The N requirement for synthesis of new dry matter of each plant organ (Nq_i, kg N $ha^{-1}d^{-1}$) is then expressed as follows:

$$Nq_i = (Cv_i / CQ_i)\, FN_i \tag{9}$$

where Cv_i is the rate of glucose available for synthesis of new dry matter of an organ *i*, and CQ_i is the inverse of growth efficiency and defined as glucose required to synthesize a unit of dry matter of the organ *i* (kg glucose kg_{DM}^{-1}). Total rate of N requirement by the crop (*Nqt*, kg N ha^{-1} d^{-1}) is the total amount of N required in order to convert all of glucose available into new dry matter, each organ with each specified FN_i.

$$Nqt = \sum_{i=1}^{n} Nq_i \tag{10}$$

N availability from remobilization and uptake

The extent to which the N requirement by the crop can be fulfilled depends on the availability of N in a common pool. The concept of single common pool of N is based on observations of cyclic translocation of amino-N via the xylem-phloem cycle path (Pate et al., 1979; Simpson et al., 1982), and was proposed by Cooper and Clarkson (1989). It was further suggested that amino-N in the common pool could be drawn upon by the demand of both shoot and root. N of amino acids derived from protein breakdown may re-enter into common pool while their carbon is used as a substrate for respiration (Durzan and Steward, 1983). The concept of a common pool is implemented in the present work. The original source of N, either from root uptake or remobilization from other parts, is assumed to have no further relevance after N has entered this common pool.

The availability of N in the common pool is primarily determined by the rate of N uptake. When the rate of N required for synthesis of new dry matter cannot be met by N available in the pool, remobilization of N from the tissue is induced, and leads to accelerated senescence of the tissue. Sinclair and De Wit (1976) suggested that redistribution of N and carbohydrates from leaves is the major cause of senescence in leguminous crops. Marshall and Porter (1991) also indicated that leaf senescence is the first to be affected by the deficiency of N. Leaf senescence of rice variety Sasanishiki was delayed up to 20 days with optimum supply of N (Makino et al., 1984). Up to 60% of N in a growing leaf can be derived from the remobilization of N (Mae and Ohira, 1981)

The rate of N remobilization from existing tissue (*Nm*, kg N ha^{-1} d^{-1}) is described as a function of the relative amount of N available in the tissue, and the deficit between N required by the crop and that available from the root uptake.

$$Nm = \frac{(\overline{FN} - \overline{FN}min)}{(\overline{FN}max - \overline{FN}min)}(Nqt - Nu) \tag{11}$$

where $\overline{FN}min$ is the residual fraction of N in a senescent tissue (kg N $\mathrm{kg}_{\mathrm{DM}}^{-1}$), and *Nu* is the rate of N uptake by roots (kg N ha^{-1} d^{-1}).

In the above expression, the difference (*Nqt-Nu*) is bound by a minimum value equal to or greater than 0. When N uptake exceeds the requirement, the difference is taken as the excess of N. The expression $(\overline{FN} - \overline{FN}min)/(\overline{FN}max - \overline{FN}min)$ represents the relative amount of N in the crop. Thus when the relative amount of N is 1, all of the deficit, *Nqt-Nu*, is satisfied by the remobilization. On the other hand, if the relative amount of N is 0.5, then only half of the deficit can be fulfilled. A similar expression was also applied by Marshall and Porter (1991) to describe the relative effect of N availability on leaf photosynthesis, tissue expansion, and senescence.

It can, however, be seen that the statement will be valid only when the relative growth rate of dry matter of the crop is less than 1.0 d^{-1}. Otherwise, the amount of N remobilized may be greater than the amount available from a tissue and lead to negative current ratio of N to dry matter, especially when the rate of N uptake by roots is 0. Nevertheless, considering that the observed maximum rate of leaf photosynthesis is 50 kg

CO_2 ha^{-1}_{leaves} d^{-1}, and 1 ha of thin leaves generally weights more than 200 kg, the maximum achievable relative growth rate is less than 0.3 d^{-1}. Therefore it is reasonable to assume that such a limitation may not be encountered in practice.

Different types of organs, as mentioned earlier, are characterized by different $\overline{FN}max$. We assume that an organ which has a higher $\overline{FN}max$ (higher N acquiring strength) also has a higher N retention strength. This is modelled with the help of the time coefficient of releasing N into the common pool during the process of remobilization. This time coefficient is smaller for an organ which has a lower $\overline{FN}max$, resulting in a faster relative release of N. The relative time coefficient is thus again applied to distinguish among the plant organ, leaves, stems and roots. The relative time coefficient of N release (Tm_i) is described as:

$$Tm_i = \overline{FN}max_i \,/\, FMIN \tag{12}$$

where *FMIN* is the lowest $\overline{FN}max$ among these organs. Total rate of N remobilization from all organs (*Nmt*, kg N ha^{-1} d^{-1}) is thus expressed as follows;

$$Nmt = \frac{\sum_{i=1}^{n} (\overline{FN}_i - \overline{FN}min_i) W_i \,/\, Tm_i}{\sum_{i=1}^{n} (\overline{FN}max_i - \overline{FN}min_i) W_i \,/\, Tm_i} (Nqt - Nu) \tag{13}$$

The rate of N availability for synthesis of new dry matter in the common pool (*Nv*, kg N ha^{-1} d^{-1}) is thus the sum of the rates of N uptake and N remobilization from all organs.

$$Nv = Nu + Nmt \tag{14}$$

The above description is summarized as follows: N uptake by the root and N present in organs of the plant act as the primary and secondary sources of N, respectively, whereas the synthesis of new dry matter is the sink. Both are connected by the cyclic common pool, representing transport systems of apoplasm and symplasm, in which N together with other solutes is circulated. The solution translocation is driven by the pressure gradient. The distribution of N is balanced by N uptake, retention strength of the secondary source, and attraction strength of the sink.

Allocation of N and glucose

When *Nv* can support all of the N required for synthesis of new dry matter, N will be allocated to all plant organs according to their requirement, and all carbohydrates available can be incorporated in synthesis of new dry matter with the required *FN*. If *Nv* exceeds the requirement by the crop, then the rate of excess (*Nx*, kg N ha^{-1} d^{-1}) is defined as follows;

$$Nx = Nv - Nqt \tag{15}$$

The cumulative amount of N left over (Wnx, kg N ha^{-1}) is the integral of Nx over time. For the time step of 1 day ($\Delta t = 1$):

$$Wnx_{(t+\Delta t)} = Wnx_t + Nx * \Delta t \tag{16}$$

In rice, when excessive amounts of ammonia have been absorbed, N excess is reserved in forms of asparagine or glutamine which are considered as the temporary storage of N (Yoshida, 1981; Magalhaes and Huber, 1989). These amino acids are also found to be the prevalent forms of nitrogenous compounds in the transport system of the plant (Ziegler, 1975). It is therefore possible that plants may store the excess amount of N in the cyclic common pool itself. However, insufficient quantitative information on the accumulation of these compounds is available to allow defining a maximum amount of N that can be accommodated in the common pool. In the present model, the amount of N excess is therefore not added to the common pool of N, but "inactivated" and integrated as a numerical check. Under normal growth conditions, such a accumulation of these amino acids may be quite low that the absence of the N buffer capability in the model would not produce a substantial consequence. Nevertheless, it will be a subject for further details investigation.

Available N is rationed in proportion to the requirement of each of the plant organs, if Nqt cannot be met by Nv. Another proportionality factor (Kp) accounts for limited N supply and is defined as:

$$Kp = Nv/Nqt \tag{17}$$

The amount of N allocated to synthesis new dry matter of each plant organ (Na_i, kg N ha^{-1} d^{-1}) is described as:

$$Na_i = Nq_i * Kp \tag{18}$$

Because new dry matter of an organ is synthesized with the required FN, thus only a proportion Kp of glucose available for growth of that organ is incorporated in the synthesis of new dry matter. The amount of carbohydrates used in synthesizing new dry matter of an organ (Ca_i, kg glucose ha^{-1} d^{-1}) is defined as:

$$Ca_i = Cv_i * Kp \tag{19}$$

where Cv_i is the rate of glucose available for synthesis of new dry matter of an organ i (kg glucose ha^{-1} d^{-1}). The excess of glucose (Cx_i, kg glucose ha^{-1} d^{-1}) that cannot be incorporated is thus:

$$Cx_i = Cv_i - Ca_i \tag{20}$$

The rate of total glucose excess is thus the sum of the rate of excesses from all organs (Cxt, kg glucose ha^{-1} d^{-1}):

$$Cxt = \sum_{i=1}^{n} Cx_i \tag{21}$$

The cumulative amount of excess glucose (Wcx, kg glucose ha^{-1}) is the integration of the difference between TCx and the rate of glucose remobilization (Cm, kg glucose ha^{-1} d^{-1}):

$$Wcx_{(t+\Delta t)} = Wcx_t + (Cxt - Cm)\,\Delta t \tag{22}$$

Wcx represents the pool of remobilizable C reserves in the form of starch, and is supposed to be stored in stems and leaf sheaths. The calculation of this reserves is carried out only after the calculation of synthesis of new dry matter of plant organs, which includes the structural part of stems. Rate of glucose remobilization is described in the next section.

The excess of glucose depends much on the growth conditions and development stage. When more N is absorbed, a higher proportion of glucose is consumed in the synthesis of amino acids and proteins. Consequently, less glucose is accumulated as reserves (Yoshida, 1981). The accumulation of glucose excess may also increase under unfavourable growing conditions such as nitrogen deficiency, water shortage, or during the period when the demand of carbohydrates for growth is relative low such as during the period prior to anthesis (Van Keulen, 1991). Thus, carbohydrate accumulation is the net balance of the growth process, consisting of two basic functions, canopy photosynthesis and the N uptake. The present work however assumes no sink limitation, that is, as far as N is not limiting, all glucose available can be incorporated into new dry matter. Therefore, it is possible that the amount glucose excess is underestimated, especially during the period of anthesis. Including a glucose sink limitation would impose that the requirement of glucose for synthesis of new dry matter be quantified for different stages of crop development.

Remobilization of reserve carbohydrates

Excess of glucose generally accumulates in the form of starch in leaf sheaths and culms of rice, and can subsequently be remobilized for growth of the crop, especially during grain filling stage (Yoshida, 1981). This can account for 20-40% of rice grain dry matter (Murata and Matsushima, 1975). To implement such findings, the potential rate of glucose remobilization (Cm, kg glucose ha^{-1} d^{-1}) from the reserves pool (Wcx, kg ha^{-1}) is described as:

$$Cm = Wcx \,/\, Tcm \tag{23}$$

where *Tcm* is the time coefficient of glucose remobilization from the reserves pool. Presently an arbitrary value of 1 d was chosen. A *Tcm* value equal to one time step only implies that potentially all reserve starch can be remobilized. However, for instance, if *Nv* is only enough for synthesis of new dry matter from glucose which is derived from current photosynthesis (Cp, kg glucose ha^{-1} d^{-1}), then none of Cm will be used, and simply return back to the pool in the form of Cx. In effect, no net remobilization occurs.

Glucose availability for synthesis of new dry matter (Cv, kg glucose ha^{-1} d^{-1}) is thus defined as:

$$Cv = Cp + Cm \tag{24}$$

The pattern of the partitioning of remobilizable glucose for growth of plant organs is assumed to follow that of the current assimilated glucose. However, only information on net dry weight accumulation per organ is available to use as a basis to derive the pattern of glucose partitioning. The observed net dry weight of stems, to a greater or lesser extent, consists of structural part, and of reserved starch which is the sum of glucose excess from the allocation for growth of each plant organs. Therefore, to derive the pattern of glucose partitioning to each organ directly from the observed net dry weight accumulation will result in overestimating the fraction of glucose partitioned to structural (non-reserve) stem material while underestimating the fraction of glucose available to the other organs. Because information on the observed fraction of glucose partition to the structural stem weight is not available, therefore a correction factor of partitioning pattern (CF) has to be deduced from the fraction of simulated structural dry matter of stems (Wst, kg ha^{-1}) in total stem weight ($Wst+Wcx$). CF is applied to correct the partitioning of remobilized glucose only, and is expressed as:

$$CF = Wst/(Wst+Wcx) \tag{25}$$

If Cp_{st}, and Cp_j are current assimilated glucose available for synthesis of new dry matter of stems and the other organs (kg glucose ha^{-1} d^{-1}), then the availabilities of carbohydrates derived from remobilization to form structural stem dry matter (Cm_{st}, kg ha^{-1} d^{-1}) and the others (Cm_j, kg ha^{-1} d^{-1}) are as follows:

$$Cm_{st} = Cm * (Cp_{st}*CF / (Cp_{st}*CF + Cp_j)) \tag{26}$$

$$Cm_j = Cm * (Cp_j / (Cp_{st}*CF + Cp_j)) \tag{27}$$

Thus, total glucose available for synthesis of new dry matter of organ i (Cv_i) is the sum of the current assimilated glucose (Cp_i) and that from reserve pool (Cm_i), which is available to organ i.

$$Cv_i = Cp_i + Cm_i \tag{28}$$

Synthesis of dry matter for growth

Glucose and N that can be used for synthesis of new dry matter were defined earlier as the allocated glucose (Ca_i) and allocated N (Na_i) for synthesis of new dry matter. Allocated glucose and N is converted into new dry matter of organs according to their biochemical constituents. The approach applied in the conversion of glucose and N into dry matter is based on the following assumptions:

1 The amount of N allocated is entirely incorporated into protein, thus change in the fraction of N in dry matter is associated only with change in fraction of protein content in dry matter.

2 The fractions of each biochemical constituent per unit of bulk non-protein mass is constant. These constituents are carbohydrates, lipids, lignins, organic acids, and minerals.

The procedures for conversion are as follows: If N allocated for synthesis of new dry matter of an organ *i* is Na_i, an` *FNpro* is the fraction of N in protein (kg N kg^{-1} protein), then the amount of protein produced in new dry matter of organ *i* ($Gpro_i$, kg protein ha^{-1} d^{-1}) is:

$$Gpro_i = Na_i / FNpro \tag{29}$$

The amount of glucose used to produce an amount $Gpro_i$ of protein ($Cpro_i$, kg glucose ha^{-1} d^{-1}) is:

$$Cpro_i = Gpro_i * CQpro \tag{30}$$

where *CQpro* is the amount of glucose required to produce a unit of protein (kg glucose kg^{-1} protein). If glucose allocated for growth of the organ *i* equals Ca_i (kg glucose ha^{-1} d^{-1}), then the amount of non-protein in new dry matter of organ *i* ($Gnonp_i$) is:

$$Gnonp_i = (Ca_i - Cpro_i) / CQnonp_i \tag{31}$$

where $CQnonp_i$ is the amount of glucose requirement to produce one unit of non-protein part of organ *i* (kg glucose kg^{-1} non-protein). Total new dry matter of organ *i* (G_i, kg ha^{-1} d^{-1}) is the sum of protein and non-protein part, which equals to

$$G_i = Gpro_i + Gnonp_i \tag{32}$$

The amount of glucose required to produce a unit of non-protein dry matter of organ *i* ($CQnonp_i$, kg glucose $\text{kg}^{-1}_{\text{non-protein}}$) is described as

$$CQnonp_i = \frac{\sum_{j=1}^{n} CQ_i ZF_{ij}}{\sum_{j=1}^{n} ZF_{ij}} \tag{33}$$

where CQ_j is the amount of glucose required to produce a unit of a biochemical component *j* of non-protein part of organ *i* (kg glucose kg^{-1}), and ZF_{ij} is the amount of component *j* in a unit of non-protein part of the organ *i* (kg DM_j $kg^{-1}_{non-protein}$).

Respiration due to growth of an organ *i* (CO_{2_i}, kg CO_2 ha^{-1} d^{-1}) is complementary to the conversion coefficient:

$$CO_{2_i} = (Gpro_i * CO_2pro) + (Gnonp_i * CO_2nonp_i) \tag{34}$$

and:

$$CO_2nonp_i = \frac{\sum_{j=1}^{n} CQ_i ZF_{ij}}{\sum_{j=1}^{n} ZF_{ij}} \tag{35}$$

where CO_2pro and CO_2nonp_i are the amount of CO_2 respired to produce a unit of protein (kg CO_2 kg^{-1} protein) and a unit of non-protein part (kg CO_2 kg^{-1} non-protein) respectively, and CO_{2_j} is the amount of glucose respired to produce a unit of biochemical component *j* of the non-protein part (kg CO_2 kg^{-1}).

Biochemical compositions of the organ are different among leaves, stems, panicles and grains, and roots. The synthesis of new dry matter of each of them are calculated separately, and each in turn. The procedures for calculating growth and associated respiration of the organ are calculated by the subroutines DMPRO, GLRXS, and CO2XS. The constant values, *FNpro*, *CQpro*, CQ_j, CO_{2_j}, and ZF_{ij}, are taken directly from the average values as estimated by Penning de Vries et al., (1989). Details of the corresponding calculations are given in Pannangpetch and ten Berge (1994).

The calculation procedure of the above described algorithm is reversed and applied to calculate the amount of glucose required to produce a unit of dry matter with a specified fraction of N which can be ranging from 0.0 to 0.15. The glucose requirement for growth (*CQ*) is the inverse of growth efficiency as mentioned earlier. The calculation of glucose requirement for growth is calculated by the subroutine SUCRG, details of which are given in Pannangpetch and ten Berge (1994). The subroutine is used by the model; but it is also used -for this study only- to generate boundary conditions of daily glucose input from observed dry matter.

Input data

Inputs are classified into system parameters (i.e. characteristics remaining constant during simulation), and driving variables. The constant values are further divided into generic ones, similar for most of the rice varieties, and specific ones. The generic input constants are used in the description of growth at a basic process level. They include parameters used in the calculation of growth efficiency, synthesis of dry matter, and respiration for growth. The specific input constants are crop parameters. They may be considered as the properties specific of a variety, and are responsible for varietal differences in the response of the crop to the external driving variables, such as total N uptake. These constants are the maximum fraction of N to dry matter of an organ, and the residual fraction of N to dry matter in the senescent organ. They are declared through an input file. Driving variables are those that change with time and are independent from the relation specified in the model. Details and values of these constants and driving variables are given in Pannangpetch and ten Berge (1994).

Generation of boundary conditions for testing the model

The validity of the model in describing the behaviour of the system and its responses to the external variables depends on whether essential relationships among the components of the system and their interactions to the external driving variables have been included and described properly. In order to test a model, possible sources of error other than within the tested model have to be minimized. In the present work, the simulated processes are N allocation, the synthesis of new dry matter of plant organs and the formation of reserves. The inputs required by the model are (a) the rate of total N uptake, and (b) the rate of glucose production for growth of each plant organ. To eliminate the possibilities of interference from the other sources, these inputs, (a) and (b) are thus derived directly from the observed data. The simulated results of N allocation and dry matter production of each plant organ are subsequently compared with the original observed values.

The rate of N uptake is derived from the observed time-course of total amount of N in the crop. The other input required by the model is the rate of glucose availability for synthesis of new dry matter of each plant organ. It is derived from the observed time-course of dry matter increases of each plant organ and the composition (N content) of the organ. These two inputs, N uptake at whole crop level and glucose availability at organ level, are presently considered as the dynamic driving variables to which the modelled system is subjected. Note that, unlike the boundary conditions, the parameters are not derived from any of these data sets.

These observed data sets are obtained from the experiments conducted at various sites in rice growing countries (Table 1). A general description of these observed data can be made as follows. The dry matter of vegetative organs attains its maximum around the period of flowering, during which the rate of crop total N accumulation also reaches a maximum. As the crop approaches maturity, the weight of dry matter of the vegetative organs generally declines due to the loss of dead tissue and redistribution of reserved materials. Decreases of total cumulative N are also observed, particularly with the data obtained from the experiments with high rates of N application. Such decreases in the amount of N are, in some cases, more than what could be accounted for by the loss of dead tissue alone. We need, however, for developing and testing the current model, only the net increase in dry weight to assess the glucose influx at each organ level. The possible occurrence of effluxes is not treated in the present study. Therefore the observed decreases of organ dry matter and total crop N accumulation are ignored.

Fifteen data sets are used to derive driving variables as inputs for the model. The same sets are also used for validating the model. They are summarized in Table 1. In view of the confounding of inputs and outputs, we will carefully expose which variables are still acceptable as indicators of model validity.

Data set No.1, unpublished data, is obtained from R. Torres, International Rice Research Institute, The Philippines, with IR58109-113-3-3 new line, Data set No 2. from K. Pannangpetch (1993). Data set No 3-7 from T.M. Thiyagarajan (1991), and No. 8-15, unpublished data, from M.N. Budhar, Tamil Nadu Rice Research institute, Tamil Nadu, India.

Identical parameter values are used for data set No.1 through No. 7. These are $F\overline{N}max_{lv}$, $F\overline{N}max_{st}$, $F\overline{N}max_{so}$, $F\overline{N}max_{rt}$, and $F\overline{N}min_{lv}$, $F\overline{N}min_{st}$, $F\overline{N}min_{so}$, $F\overline{N}min_{rt}$, acronyms of maximum fraction of total N to total dry matter of leaves, stems, storage organ, roots, and residual fraction of N to dry matter in the senescent leaves, stems, storage organ, and roots, respectively. Their values were derived from Penning de Vries et al., (1990). For the variety ADT38, it was however noted that the fraction of total N to total dry matter of stems and grains are notably higher than for the other varieties. Therefore $F\overline{N}max_{st}$ was increased from 0.04 to 0.05, and $F\overline{N}max_{so}$ from 0.015 to 0.018.

These input data were arranged according to the format required by FSE, Fortran Simulation Environment, (Kraalingen, 1991). Simulation started on the first sampling date after transplanting.

Table 1. Data used in deriving driving variable inputs and for validation of the model.

Data	Variety	Experimental side	Year	N treatments
Set 1	IR (New line)	IRRI, Philippines	1991	0 kg N ha^{-1}
Set 2	RD6	K.K.U., Thailand	1991	120 kg N ha^{-1}, Pot Exp.
Set 3	ADT39	TNRRI, India	1990	0 kg N ha^{-1}
Set 4	ADT39	TNRRI, India	1990	100 kg N ha^{-1}
Set 5	ADT39	TNRRI, India	1990	200 kg N ha^{-1}
Set 6	ADT39	TNRRI, India	1990	300 kg N ha^{-1}
Set 7	ADT39	TNRRI, India	1990	400 kg N ha^{-1}

Table 1 continued next page

Table 1 continued

Data	Variety	Experimental side	Year	N treatments
Set 8	ADT38	TNRRI, India	1992	0 kg N ha^{-1}
Set 9	ADT38	TNRRI, India	1992	100 kg N ha^{-1}, (Fertilizer)
Set 10	ADT38	TNRRI, India	1992	50 kg N ha^{-1}, (Fertilizer) + +50 kg N ha^{-1}, (Green manure)
Set 11	ADT38	TNRRI, India	1992	100 kg N ha^{-1}, (Green manure)
Set 12	ADT38	TNRRI, India	1992	200 kg N ha^{-1}, (Fertilizer)
Set 13	ADT38	TNRRI, India	1992	100 kg N ha^{-1}, (Fertilizer) + +100 kg N ha^{-1}, (Green manure)
Set 14	ADT38	TNRRI, India	1992	200 kg N ha^{-1}, (Fertilizer)
Set 15	ADT38	TNRRI, India	1992	150 kg N ha^{-1}, (Fertilizer) + + 68 kg N ha^{-1}, (Green manure)

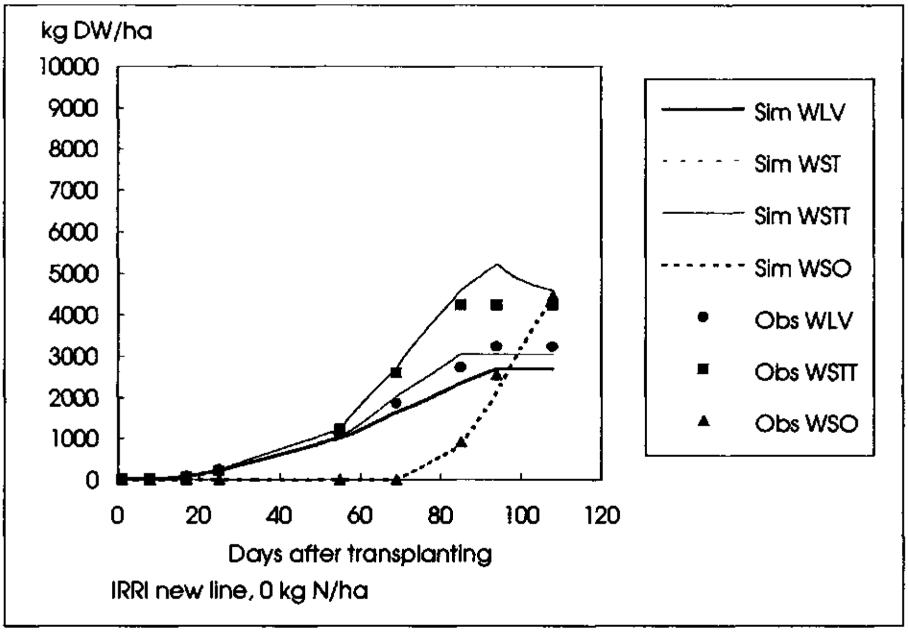
Results and discussion

The results of simulated N allocation, expressed as fraction of total N content in dry matter, and the dry matter of each plant organ were compared to the observed values. Typical cases are presented in Figures 2 to 5. Figures for all sets are given by Pannangpetch and ten Berge (1994).

Allocation of N

Simulation of tissue N content

During the vegetative phase and early reproductive phase, there are close relationships between observed and simulated fractions of N content in the tissues. The differences between simulated and observed values are generally less that 0.005 kg N kg_{DM}^{-1} of N fraction. In few cases, the differences can approach, but not exceed, 0.01 kg kg^{-1}. However, during the later stage of reproductive phase, especially 20 days prior to maturity, there are large differences, 0.017 kg N kg_{DM}^{-1}, between simulated and the observed value. The discrepancy is more readily observed with the fraction of N in leaves, and grains from data set No. 5-7 which were obtained from experiments with high N application. For these sets, simulated N fraction of leaves is higher than the observed value, while N fraction of grains is lower. This reflects the increases in the rate of N remobilization from leaves due to the spontaneous process of senescence as the plant approaches maturation. The increases in N remobilization from senescent tissue will lead to higher level of N availability for growth of grains than the estimated level, and may be responsible for the observed net N loss from the plants, especially with high rates of N application.



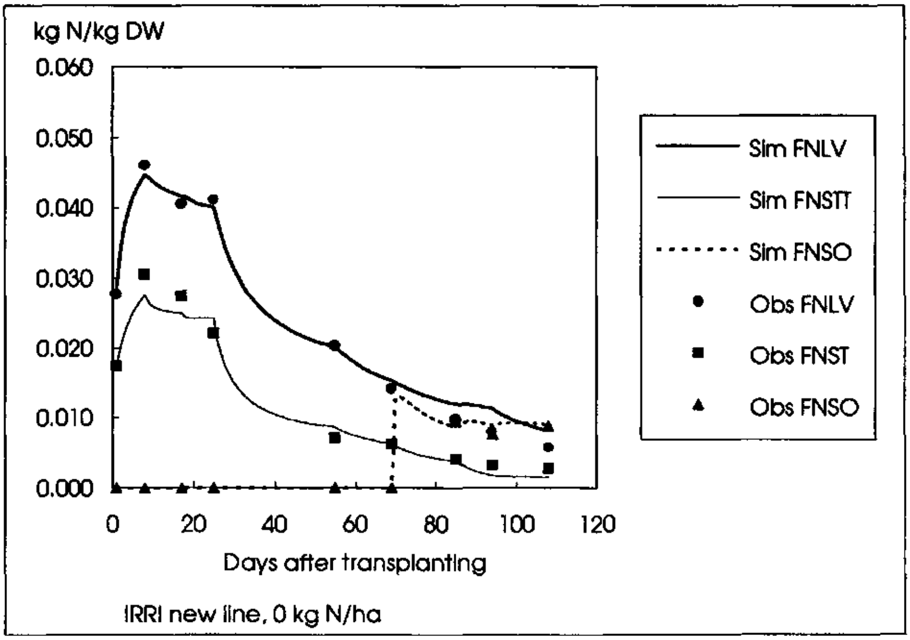
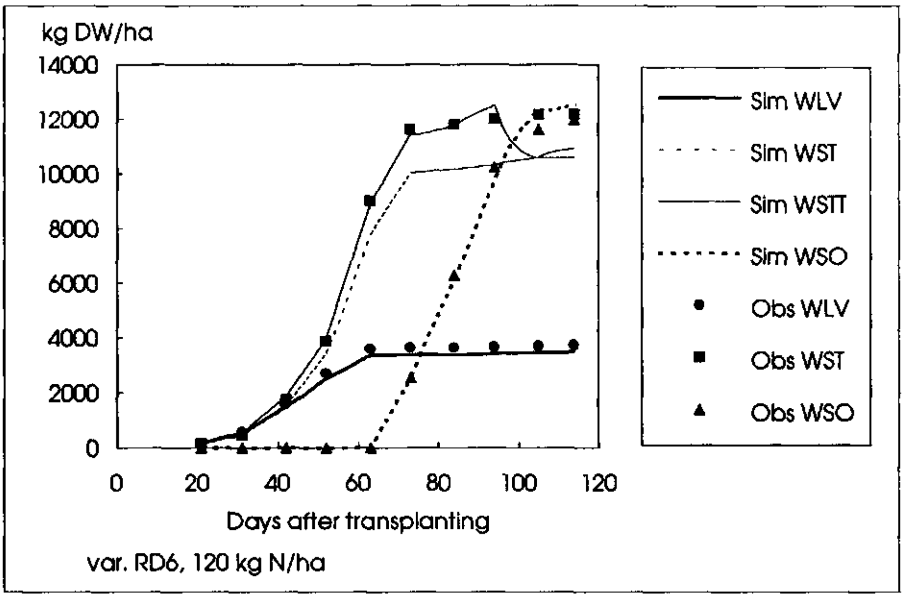


Figure 2. Top: observed and simulated dry weight of leaves (WLV), stems including reserves (WSTT), and panicles including grains (WSO). Only simulations, no observations, are available of stem mass excluding reserves (WST). Bottom: observed and simulated mass fractions of N in leaves (FNLV), stems including reserves (FNSTT), and panicles including grains (FNSO). Dataset IRRI 1991, new line, 0 kg N/ha.



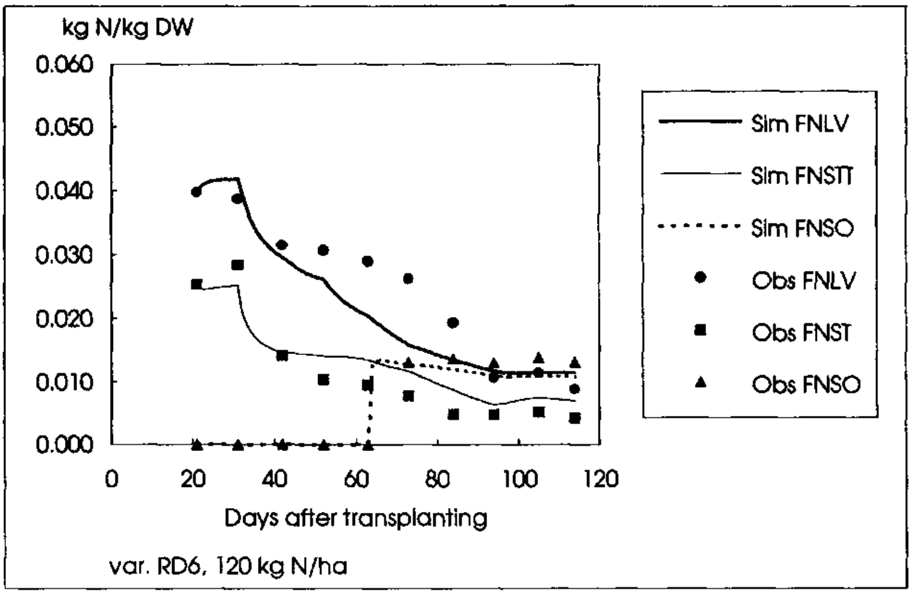


Figure 3. Top: observed and simulated dry weight of leaves (WLV), stems including reserves (WSTT), and panicles including grains (WSO). Only simulations, no observations, are available of stem mass excluding reserves (WST). Bottom: observed and simulated mass fractions of N in leaves (FNLV), stems including reserves (FNSTT), and panicles including grains (FNSO). Dataset Khon Kaen University, 1991, cvar RD6, 120 kg N/ha, pot experiment.

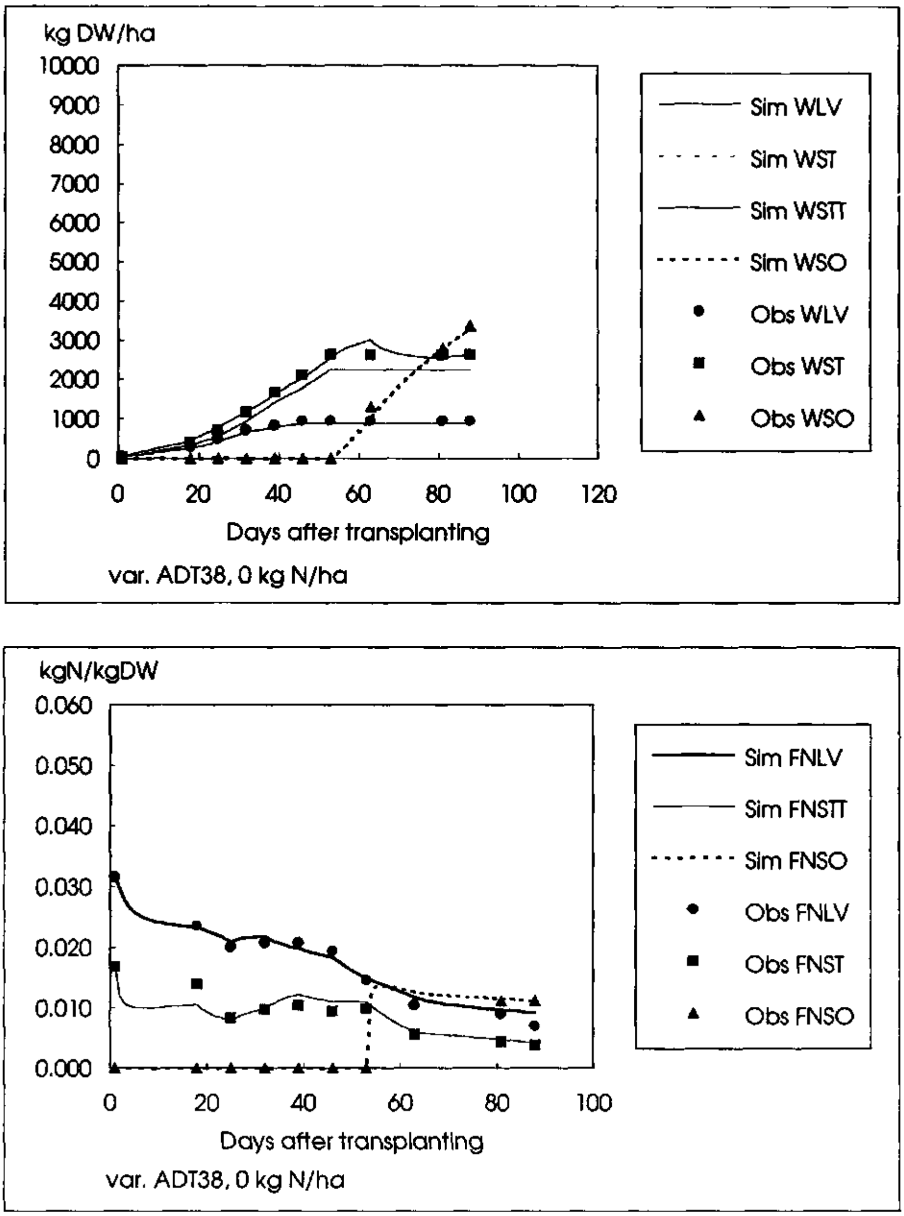
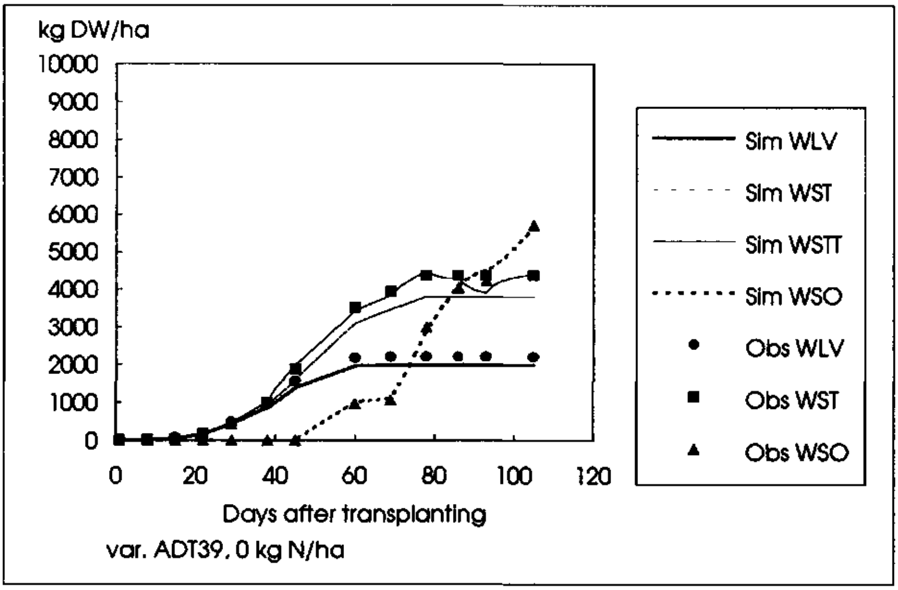


Figure 4. Top: observed and simulated dry weight of leaves (WLV), stems including reserves (WSTT), and panicles including grains (WSO). Only simulations, no observations, are available of stem mass excluding reserves (WST). Bottom: observed and simulated mass fractions of N in leaves (FNLV), stems including reserves (FNSTT), and panicles including grains (FNSO). Dataset Tamil Nadu Rice Research Station 1992, cvar ADT38, 0 kg N/ha.



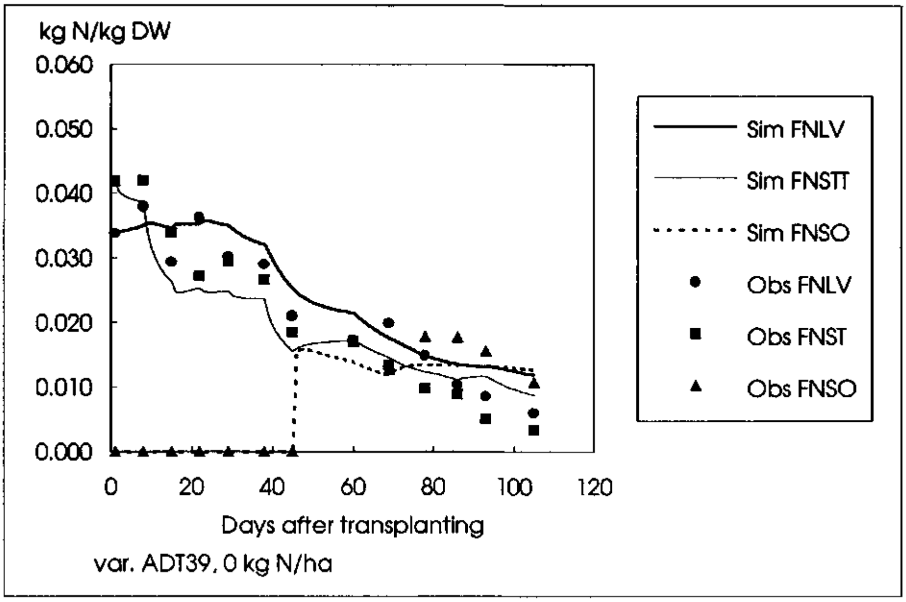


Figure 5. Top: observed and simulated dry weight of leaves (WLV), stems including reserves (WSTT), and panicles including grains (WSO). Only simulations, no observations, are available of stem mass excluding reserves (WST). Bottom: observed and simulated mass fractions of N in leaves (FNLV), stems including reserves (FNSTT), and panicles including grains (FNSO). Dataset Dataset Tamil Nadu Rice Research Station 1990, cvar ADT39, 0 kg N/ha.

Effect of tissue senescence

Although the effect of spontaneous tissue senescence is not included in the present model, we mention its mechanisms and effects as a basis for future improvements. Prior to maturity, most of the vegetative tissues enter the phase of senescence associated with increasing activities of proteolytic enzymes, and concurrently decreasing in the integrity of the cellular organelles and membranes (Stoddart and Thomas, 1982; Zimmermann, 1969; Steveninck 1976). Subsequently, products of the breakdown processes may accumulate in the common pool, and becomes more readily for growth of grains. Synthesis of new dry matter for growth of grains during this period can be under 'N-saturated state'. This accumulation of the breakdown products may also lead to net N loss from the plant. At least two mechanisms have been identified. Accumulation of breakdown products in the common pool will increase the concentration gradient of N across the membrane of the root. Together with the increases in permeability of the membrane to the passage of solutes, and decreasing mitochondria activities to generate sufficient energy to maintain the concentration gradient, an increase in the efflux from the root could follow, and result in net loss of N from the crop. Furthermore, the rate of N volatilization from leaves may also increase due to a declining activity of glutamine synthetase which is responsible for reassimilation of ammonia released during senescence (McNally et al., 1983; Thimann, 1980). Gaseous losses of NH_3 can be up to 75 kg N ha^{-1} in 10 weeks (Wetselaar and Farquhar, 1980; Farquhar et al., 1983). It was further pointed out that such losses are highest for plants with high N contents and take place mainly between anthesis and maturity.

Simulation of N excess

The accumulated amount of N excess was calculated for each simulation as a numerical check. N excess was observed with only four data sets, No 1, 9, 12, and 15. The highest value was 0.29 kg N ha^{-1} with the data Set No 12. Because the total N input was the total net N assimilated by the crop, the amount of N excess is entirely attributed to numerical error in the calculation. Therefore, the amount of N excess is not returned into the common pool of N for any further use in the synthesis of new dry matter. Nevertheless, the consequence of this N excess on crop growth was evaluated by returning the excess into the common pool and making available for growth. The increase in total crop dry weight was less than 10 kg ha^{-1} at the harvest. Therefore, the numerical error can be ignored.

As explained, the present model does not allow for storage of excess N. Whenever it may occur during simulation, such excess N is 'taken out' or 'inactivated' It has been suggested that the short term regulation of net uptake of N is based on the efflux, not the influx regulation (Cram, 1988). The rate of N influx would then always be kept at the maximum level allowed under the given external conditions. Considering that N content in a plant organ is generally lower than the maximum, and that N is always remobilized from the older tissue, it seems unlikely that N efflux from the roots is common. Moreover, as more N is incorporated into dry matter, especially of leaves, photosynthesis is increased and this results in higher glucose availability for synthesis of new dry matter. This positive feedback mechanism would prevent the accumulation of excess N. Nevertheless, N efflux might occur under specific situations. Such conditions could occur at the very early stage of growth when growth rate is low, or during maturation when N release from senescent tissue is high, or before anthesis when total sink strength for N and glucose may be low, or just after excessive N application during which N concentration in soil solution is abruptly increased. Under these conditions, if a high buffering capacity for N would exist in reality, ignoring this buffer could lead to underestimation of growth. It is, however, not included now because not sufficient quantified information is available.

Synthesis of dry matter

Simulation of organ dry matter

Because the amount of glucose available for synthesis of new dry matter is derived from observed time-courses of dry matter increases of plant organs, simulated dry matter of an organ will also be in close agreement with the observed values, if the rates of N requirement and remobilization for synthesis new dry matter of an organ are estimated correctly. On the other hand, if N requirement is overestimated and/or N remobilization is underestimated, only a fraction of glucose available can be incorporated into new dry matter due to limited N availability. The remaining glucose would be diverged into reserves pool of carbohydrates. Consequently, dry matter of a plant organ would be underestimated while glucose excess would be overestimated.

Simulated weights of plant organs show close resemblance to those of the observed values. Generally the differences were less than 10% at harvest. The exception was that of leaf dry weight from the data set No.1, in which simulated value was 15% less than the observed value. This can be attributed to overestimation of the rate of N requirement for synthesis of new leaf dry matter, so that N required for leaf growth was not be fully satisfied and resulted in underestimation of leaf growth. Indeed it is seen from Figure 1. that sum of the simulated structural stem weight and reserved glucose is higher than the observed stem weight which always refers to both structural dry matter plus reserves.

Simulation of reserve carbohydrate

The simulated amount of excess cumulated glucose was compared with the corresponding values derived directly from observations. The latter values were assessed based on the assumption that the real plant stored all reserves in stems and leaf sheaths (in the form of starch), and that this amount can be identified as the difference between the observed maximum total stem weight (around the time of flowering) and the observed minimum value well after flowering.

The simulated values of carbohydrate excess are presented for the date at which the observed maximum total stem weight was recorded, usually just before flowering. The amount of the reserve was expressed as the percentage of the total stem dry weight, ie. the weight of structural stem tissue plus the reserves. The relationship between the estimated

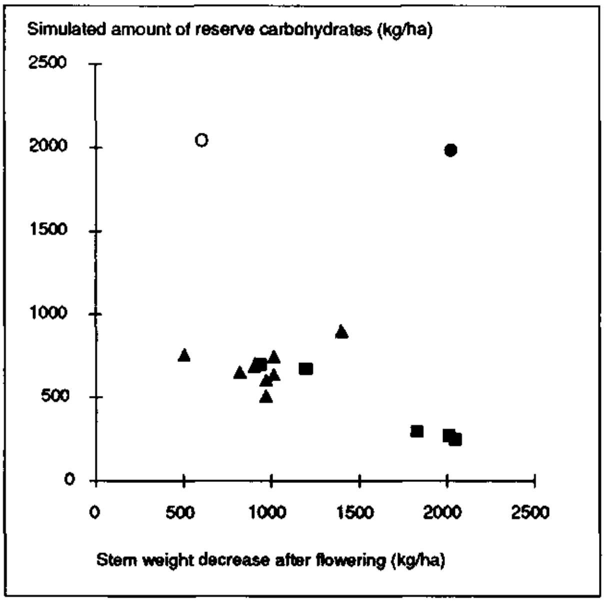


Figure 6a. The relation of simulated weight of reserve carbohydrates and observed weight of stem decreases after flowering. Solid circle is from data set No. 1, open circle from No. 2, square from No. 3-8, and triangle from No. 9-15.

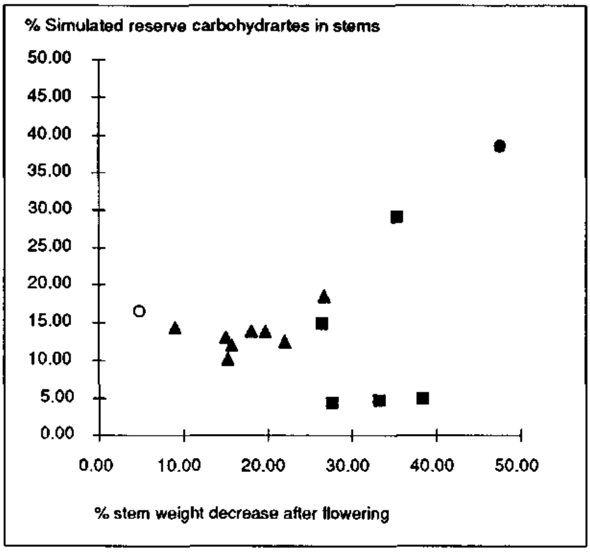


Figure 6b. The relation of simulated weight of reserve carbohydrates and observed weight of stem decreases after flowering expressed as % of total stem weight, structural stem weight plus reserve. Solid circle is from data set No. 1, open circle from No. 2, squares from No. 3-8, and triangles from No. 9-15.

values and the observed values is presented in Figure 6. The values of simulated reserve were between 5 to 40%. The figure confirms the general principle that relatively higher starch accumulation occurs under N-limited conditions (Yoshida, 1981). In only four cases, the simulated values deviated strongly from the observed ones. These are data set No. 2, 5, 6, and 7. The data set No. 2 was obtained from pot experiment with high N application and high penetration of light into the crop canopy. Under such conditions, it is likely that the current photosynthates and N uptake by the crop could meet most of the requirement for growth of the grains. Consequently, relatively low amounts of glucose may have been drawn from the stem reserves, which has led to underestimation of the real size of the reserve pool, because of the method of experimental assessment of this pool size. Data set No. 5, 6, and 7 were obtained from field experiments with high N application. The relative availability of N may have been quite high so all glucose available was simulated to be incorporated into new dry matter. The current model includes no limitation to the rate of new dry matter synthesis. In reality, however, such maximum rate may exists, especially during the time prior to anthesis.

Had such a sink limitation been included in the model, then excess accumulation of both carbohydrates and nitrogen could occur. The possibility of retaining excess N in the plant would then depend on the buffer capacity of the N-common pool.

Suggestions for future work

From the above discussion, we conclude that there are three 'gaps' for further work that could lead to improvements in the performance of the present model. These are the mechanistic description and quantification of: (1) the N buffering capacity, (2) spontaneous tissue senescence, and (3) the maximum requirement of glucose for growth, especially during the period prior to anthesis.

Listing of symbols and the corresponding acronyms as used in the subroutines

Symbols	Acronyms	Descriptions
N requirement		
Nq_i	NRQG (LV, ST, SO, RT)	N required for growth of plant organ i, consisting of leaves, structural stem, storage organ, and root kg N ha^{-1} d^{-1}
Nqt	NRQGCR	N required for growth of crop, equal to the sum of Nq_i
FN_i	FNG(LV, ST, SO, RT)	Fraction of N in dry matter to be synthesized during a time interval of organ i; leaves, stems, storage organs, and roots kg N kg^{-1}
$\overline{FN}_i$	FN(LV, ST, SO, RT)	Current fraction of N in organ i; leaves, stems, storage organ, and roots kg kg^{-1}
G_i	G(LV, ST, SO, RT)	Growth in dry matter of organ i, consisting of leaves, stems, storage organs, and root kg ha^{-1} d^{-1}
Cv_i	TCAG(LV, ST, SO, RT)	Total carbohydrates available for growth of organ i; leaves, stems, storage organs, and roots kg ha^{-1} d^{-1}
CQ_i	CRG(LV, ST, SO, RT)	Carbohydrates required for synthesis a unit of dry weight of organ i; leaves, stems, storage organs, and roots kg kg^{-1}
GE^{-1}		Inverse of CQ_i
FN max	MXFNG	Maximum potential fraction of N in tissues to be synthesized during a time interval; equal for all plant organs kg N kg^{-1}
$\overline{FN}\max_i$	MXFN(LV, ST, SO, RT)	Maximum potential fraction of N in organ i; leaves, stems, storage organs, and roots kg N kg^{-1}
Tq_i	RTCN(LV, ST, SO, RT)	Relative time coeffcient of N acquisition of organ i; leaves, stems, storage organs, and roots d d^{-1}
FMAX	FMAX	Reference to derived relative time coeffcient for N acquisition among tissues, being equal to the highest value of $\overline{FN}\max_i$
Kp	NAQ2RM	Relative N acquisition time to N remobilization time d d^{-1}

N availability from remobilization and uptake

Nu	NUPT	Total crop N uptake kg N ha^{-1} d^{-1}
$\overline{FN}\mathrm{min}_i$	RFN(LV, ST, RT)	Residual fraction of N in dead tissue of organ i; leaves, stems, and roots (For storage organ variable MNFNSO is used instead of RFNSO) kg N kg^{-1}
W_i	W(LV, ST, SO RT)	Current dry weight of organ i; leaves, stems, storage organs, and roots kg ha^{-1}
FMIN	FMIN	Reference to derive relative time coefficient for N remobilization among organs, equal to the lowest values of $\overline{FN}\mathrm{max}_i$ among the organ kg N kg^{-1}
Tm_i	RTCN(LV, ST, SO, RT)	Relative time coefficient of N remobilization from organ i; leaves, stems, storage organs, and roots d d^{-1}
Nm_t	NRMCR	N remobilization from crop kg N ha^{-1} d^{-1}
Nv	TNAG	Total N available for growth of crop kg N ha^{-1} d^{-1}

Allocation of N and glucose

Nx_t	NXCESS	Excess of N due to limitation of carbohydrates available kg N ha^{-1} d^{-1}
Wn_x	NLO	Cumulative N excess from tissue synthesis kg N ha^{-1}
Kp	PPFAC	Proportioning factor for allocation of glucose and N
Na_i	NA(LV, ST, SO, RT)	N allocated for growth of organ i; leaves, stems, storage organs, and roots kg N ha^{-1} d^{-1}
Ca_i	CAG(LV, ST, SO, RT)	Carbohydrates allocated for growth of organ i: leaves, stems, storage organs, and roots kg ha^{-1} d^{-1}
Cx_t	CXCESS	Excess of carbohydrates due to limitation of N available kg ha^{-1} d^{-1}
Wc_x	WSTR	Cumulative dry weight of carbohydrates reserved in stem kg ha^{-1}
Cm	CRMCR	Remobilizable carbohydrates available for crop growth kg ha^{-1} d^{-1}

Remobilization of reserve carbohydrates

Tcm	TCPCRM	Time coefficient of maximum remobilization of glucose from reserves pool in stems	d
Cp_{st}	ACGST	Photosynthetically assimilated carbohydrates available for growth of stems	kg ha^{-1} d^{-1}
Cp_j	ACG(LV, SO, RT)	Photosynthetically assimilated carbohydrates available for growth of organ j; leaves, storage organs, and roots	kg ha^{-1} d^{-1}
W_{st}	WST	Current dry weight of structural stems	kg ha^{-1}

Synthesis of dry matter for growth

FNpro	FNPRO	Fraction of N in protein, average value	kg N kg^{-1}
CQpro	GLRPRO	Glucose required for synthesis a unit of protein	kg kg^{-1}
$Gpro_i$	G(LVP, STP, SOP, RTP)	Growth of organ i, leaves, stems, storage organs, and roots, due to protein	kg ha^{-1} d^{-1}
$Cpro_i$	CAG(LVP, STP, SOP, RTP)	Carbohydrates allocated for growth of protein part in organ i; leaves, stems, storage organs, and roots	kg ha^{-1} d^{-1}
$Gnonp_i$	G(LVS, STS, SOS, RTS)	Growth of organ i, leaves, stems, storage organs, and roots, due to non-protein part	kg ha^{-1} d^{-1}
G_i	G(LV, ST, SO, RT)	Growth of organ i; leaves, stems, storage organs, and roots	kg ha^{-1} d^{-1}
$CQnonp_i$	GLR(LVS, STS, SOS, RTS)	Glucose required for synthesis a unit of non-protein part of organ i; leaves, stems, storage organs, roots	kg kg^{-1}
CQ_i	GLR(CAR, FAT, LIG, ORG, ASH)	Glucose required for synthesis a unit of biochemical component j of non-protein part; carbohydrates, fats, lignins, organic acids, and minerals	kg kg^{-1}
ZF_{ii}	ZF(CAR, FAT, LIG, ORG, ASH) (LV, ST, SO, RT)	Amount of component j in a unit of non-protein part of organ i; carbohydrates, fats, lignins, minerals, in leaves, stems, storage organs, and roots	kg kg^{-1}
$CO_{2,}$	CO_2(LV, ST, SO, RT)	Respiration for growth of organ i; leaves, stems, storage organs, roots	kg CO_2 ha^{-1} d^{-1}

CO_2pro	CO_2PRO	CO_2 respired for synthesis a unit of protein kg kg^{-1}
CO_2nonp_i	CO_2(LVS, STS, SOS, RTS)	CO_2 respired for synthesis a unit of non-protein part of organ i; leaves, stems, storage organs, and roots kg kg^{-1}
CO_2	CO_2(CAR, FAT, LIG, ORG, ASH)	CO_2 respired for synthesis a unit of biochemical component j of non-protein part; carbohydrates, fats, lignins, organic acids, and minerals kg CO_2 kg^{-1}

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The ORYZA_0 model applied to optimize nitrogen use in rice

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Abstract
The simple dynamic model ORYZA_0 is introduced to simulate, on the basis of empirical coefficients, biomass production in irrigated rice under nitrogen (N-) limited conditions. The model includes N uptake, partitioning of N to the leaf canopy, and the utilization of leaf N in converting daily incident global radiation into dry matter. Input parameters include soil and crop characteristics, and four parameters defining the generalized logistic cumulative N application curve A(t) as a function of time t. Most input parameters can be derived directly from field observations.

Nine datasets from China, India and The Philippines, each including a number of N application schemes and levels, are used to demonstrate that the growth equation in ORYZA_0 accurately describes crop biomass production throughout the growing season for all treatments within a set, after a single value for p, the initial leaf nitrogen use coefficient (g g^{-1} d^{-1}), is assigned per dataset by calibration. Observed time series of N contained in the canopy per ha ground area (g m^{-2}) and daily global radiation are used as forcing functions.

The model, combined with a global search numerical optimization procedure, is used in a case study for IRRI dry season conditions to determine the optimum A(t) curve (recommendation curve) for a fixed total N input, as a basis for formulating best N management practices. The N response curve is constructed by repeating the optimization procedure for different total N input levels. The resulting response and recommendation curves appear realistic but their validity is still subject to independent field tests. Recommendation curves indicate that, for rice cvar IR72 and IRRI dry season conditions, 75% of total N input must have been applied before 40 days after transplanting have passed, irrespective of the application level. At low input levels, N dressings should be

irrespective of the application level. At low input levels, N dressings should be concentrated shortly before completion of this period. Annual fluctuations in radiation pattern affect the recommendation curve.

Introduction

Over the past five years, SARP teams have been engaged in collecting information about nitrogen (N) uptake and utilization by the rice crop. At several locations, covering various soil types and weather conditions, crop responses to N application schemes have been studied in detail. Not only were N uptake and biomass monitored by frequent sampling, also biomass and N contents of the various plant organs (leaves, stems, roots, panicles) were observed. These efforts have yielded an extensive data collection. Many of the field studies are reported in this volume.

Based on the results of such detailed studies, the various N-related sub-processes relevant to yield formation can be described quantitatively. In this paper we present the summary model ORYZA_0 to describe responses of the rice crop to N application. This is by no means an exhaustive compilation, and takes into account only part of the knowledge documented by SARP participants and available from other sources. We attempted to construct the model exclusively on the basis of parameters which can be derived from straightforward field observations of biomass and N contents. As a consequence, a few rather empirical relations are used in the model. Some of these, for example the N recovery function, are not fully understood but can nevertheless be used as site descriptors. Likewise, varietal characteristics are expressed in measurable parameters, although environmental effects on these values can not always be ruled out.

The model is applied here to derive the optimum application strategy for N fertilizer in irrigated rice, under specified varietal and environmental characteristics. This is done with the help of numerical optimization. A case study is worked out for IRRI dry season conditions.

The ORYZA_0 model

The model ORYZA_0 simulates biomass accumulation in rice as limited by nitrogen (N) uptake and daily total global radiation. It is based on a very limited set of relations expressing soil and crop processes. The equations used in describing both the soil and the crop component of the model are stripped down to the bare basics. ORYZA_0 can, therefore, be regarded as a real summary model of N limited rice growth. The complexity found in the more detailed crop growth and development models, such as ORYZA_1 and ORYZA_N, is avoided here: explicit formulations of phenological development, leaf area development, light interception, assimilation, respiration, conversion of glucose into dry matter, partitioning of dry matter, remobilization of carbohydrates, and the formation of sink size are all omitted. The net results of all these processes are expressed in a few coefficients.

Contrary to the other ORYZA models, however, ORYZA_0 includes a soil component to describe, albeit in a very empirical form, N uptake. As a consequence, more attention is also given to crop N demand as a factor which might limit N uptake.

Most of the parameters used in the model can be easily obtained from field studies, such as those already conducted by several of the SARP teams working in the theme Crop and Soil Management.

Time variables

Basic time variables are the dates of planting, first flowering (FF), and harvest. The FF stage is reached when 10% of the rice hills carry at least one flowering panicle. This is usually a week before full flowering, the stage when 90% of the hills carry at least one flowering panicle. (The time of reaching the full flowering stage is not used in ORYZA_0). The date corresponding to the FF stage, t_{FF}, marks a shift in nitrogen allocation pattern and triggers the redistribution of leaf nitrogen.

The three dates indicated are specified as parameters (inputs). For the purpose of zonation studies, where the dates of phenological events are often sought as model outputs, ORYZA_0 can easily be extended by including one of the ORYZA-modules for phenological development which then calculates flowering and maturity dates on the basis of planting date and weather variables.

Dry matter accumulation

The crop growth rate G (g m^{-2} d^{-1}) is calculated from daily incident global radiation R (MJ m^{-2} d^{-1}) and the amount of N contained in the leaf canopy, N_L , which is expressed in g leaf nitrogen per m^2 ground (!) surface area:

$$G = p\, N_L \, [1 - e^{-\varepsilon f_R R/(p N_L)}] \tag{1}$$

where p is the initial leaf nitrogen use coefficient (g dry matter produced per day and per g leaf N), ε is the initial global radiation use coefficient (g dry matter produced per MJ incident global radiation), and f_R is a radiation reduction function:

$$f_R = e^{-\alpha R} \tag{2}$$

The reduction function is introduced to account for the decrease in the productivity per unit incident radiation observed at higher radiation levels. This phenomenon is partly ascribed to light saturation at the level of individual leaves, and partly to a changing light composition, i.e. the ratio of the diffuse to the direct component. Diffuse radiation penetrates deeper into the canopy and is therefore more effective. (Obviously, Eq. 1 would also result in a decreasing productivity G/R if f_R were equal to unity, but the attenuation

The variable N_L is the 'production capital' available to the crop for converting radiation into dry matter. It replaces two other variables used separately in most crop growth models: leaf area index (LAI) and leaf nitrogen concentration (either per unit leaf surface or leaf mass). ORYZA_0 thus does not distinguish between the two processes of light interception and its subsequent utilization. As a consequence, the parameter p represents the overall efficiency by which leaf nitrogen is used in producing dry matter. Rice varieties exhibiting a high p value are thus efficient in using leaf nitrogen to produce dry matter, a characteristic that may be associated either with thin leaves (relatively high light interception per unit N_L), or with a relatively pronounced allocation of nitrogen to photosynthetically active leaf compounds. Values of p as found in this study ranged from 7 to 12 $g\ g^{-1}d^{-1}$. (See below.) The adjective 'initial' in the definition of p serves to indicate that the overall crop leaf nitrogen utilization quotient (g dry matter produced per g leaf nitrogen per day) indeed approaches the value of p at low levels of N_L. Likewise, the overall global radiation use quotient (g dry matter per MJ incident radiation) approaches ε at low radiation levels.

The numerical model uses one-day time steps to convert, by rectangular integration over time, the growth rate G to assess the course of crop biomass, $W_c(t)$ ($g\ m^{-2}$), and ultimately the total seasonal production. A fixed harvest index HI ($g\ g^{-1}$) converts total crop biomass (i.e. including root biomass) into grain yield.

Allocation and redistribution of nitrogen

Of the total amount of N taken up every day, only a fraction is allocated to the leaves. This fraction, f_{NL}, is usually stable during crop development up to the 'first flowering' (FF) stage. It thus relates N_L to total crop N uptake, N_c ($g\ m^{-2}$) and can easily be estimated from field observations at any time during this period:

$$f_{NL} = N_L/N_c \tag{3}$$

Considerable variation in f_{NL} has been observed among rice varieties. Results collected by SARP teams have shown a range of 0.40 (CR1009) to 0.55 (IR64). This parameter may well be the most discrimitative varietal property with respect to the so-called 'N-responsiveness'. The rate of N allocation to the N_L pool then follows as:

$$\frac{dN_L}{dt} = f_{NL}\frac{dN_c}{dt} \qquad \text{for } t < t_{FF} \tag{4}$$

From the onset of flowering, the growth of panicles (including grains) represents a strong sink for nitrogen. Since virtually all crop growth after FF stage is invested in panicles, the panicle N demand, dNp/dt, is the product of total crop growth rate and the fraction of N in panicles, n_p (g N per g dry matter):

$$\frac{dNp}{dt} = n_p \; G \qquad (5)$$

where Np is the total amount of nitrogen contained in panicles (g m^{-2}). The nitrogen required for allocation to panicles may be derived from the leaves, if the demand cannot be covered by direct N uptake. The rate of N extraction from leaves is supplemented with N reallocated from stems, leaf sheaths and roots. The ratio of N supply rates from these two contributing sources - leaf and non-leaf vegetative tissues, respectively - to panicles is assumed to be equal to the original partitioning coefficient, f_{NL}. The rate of N translocation from leaves is therefore:

$$\frac{dN_L}{dt} = f_{NL}\left(\frac{dN_c}{dt} - \frac{dNp}{dt}\right) \qquad \text{for } t > t_{FF} \qquad (6)$$

Translocation implies that the difference term in brackets is negative, which is usually the case after t_{FF}. Possibly, postflowering N uptake rate could exceed panicle N demand, which would render the difference term positive. When, moreover, postflowering N uptake is so large that the leaf N pool exceeds the value that had previously been attained at FF stage, additional N taken up is stored in the leaf mass only, because the capacity of roots and stems to store excess N is limited. Likewise, extraction of N from vegetative tissues for panicle growth is from leaves only at such extreme N_L levels:

$$\frac{dN_L}{dt} = \frac{dN_c}{dt} - \frac{dNp}{dt} \qquad \text{for } t > t_{FF} \text{ and } N_L > \text{at } t_{FF} \qquad (7)$$

This aspect of the model can be improved when more data become available about the relation between postflowering N uptake, panicle growth rate, and n_p, because panicles themselves also store excess nitrogen. It is known that n_p increases under conditions of high postflowering N uptake, especially when the sink size (number of spikelets per m^2) is limited. This combination of conditions will not occur under normal N management and weather conditions, but can be encountered by a crop recovering after a stress phase. Values of n_p ranging from 0.007 g g^{-1} (CR1009, Thanjavur, Tamil Nadu) to 0.015 and higher (IR72, IRRI dry season) have been observed by SARP scientists. (These values apply to whole panicles, not just grains, and are always lower than the grain N values.)

Nitrogen uptake: demand

N uptake by the crop is determined by N availability in the root zone, and the crop N demand. Demand is not a well defined concept, and includes subprocesses of various nature. We will nevertheless use it as a lumped variable which expresses all the different limitations to N uptake arising from the current state and growth rate of the crop, i.e. those limitations not directly resulting from low N availability in the bulk root zone.

During the first 20 days after transplanting (DAT), demand is exclusively governed by the relative uptake coefficient, r_N. The exponential uptake phase ends before completing the 20 d period when total crop uptake N_c reaches 3.5 g N m^{-2}:

$$\frac{dN_c}{dt} = r_N \, N_c \qquad \text{for } N_c < 3.5 \text{ and } t < 20 \text{ DAT} \qquad (8)$$

The value of r_N was found to be roughly 0.20 d^{-1}, which corresponds closely with the relative growth rate of LAI used in other models. This comes as no surprise, since specific leaf area and leaf N concentration are usually fairly constant during the first weeks of rice growth. This coefficient may be a varietal characteristic and will depend on temperature (as does leaf area development). The latter is not taken into account. For each particular case (location, variety) the value of this coefficient can be determined directly from the observed N uptake vs time, under conditions of surplus N supply (high basal application, incorporated into the soil).

The critical N_c value of 3.5 g per m^2 ground surface area corresponds roughly to LAI = 2 m^2 m^{-2} for an average young rice canopy, i.e. with a specific leaf area of 0.03 m^2 g^{-1}, leaf N content of 0.03 g g^{-1}, and f_{NL}= 0.6 g g^{-1}).

After the exponential phase, other limitations to uptake exist:

(1) Uptake rate cannot exceed a given absolute maximum value, u_N (g N m^{-2} d^{-1}).
(2) The quotient of daily N uptake to daily biomass production cannot exceed a maximum value, q_N (g g^{-1}).
(3) The maximum overall concentration of N in the total crop biomass, c_{max} (g g^{-1}), follows a pattern prescribed by the crop development stage; daily uptake cannot exceed the difference between c_{max} and the current ratio $N_c/(W_c+G)$.
(4) Uptake ceases when the size of the leaf nitrogen pool N_L reaches $N_{L,max}$ (g N m^{-2}).
(5) No N is taken up during the last week before maturity.

These parameters u_N, q_N, c_{max}, and $N_{L,max}$ will be called 'N-demand' parameters. At the moment, we do not know to what extent they vary among cultivars, soil types, and weather conditions. More insight will be attained soon, because these parameters can be determined from field observations of uptake and crop growth vs time, under non-limiting N supply; the many detailed experiments conducted by SARP teams allow such analyses. Soil effects on the values of some of these parameter should not be ruled out, even though we designated them as demand (not: supply-) limiting factors; soil factors other than those directly affecting bulk root zone N availability might limit the N uptake ability of the root system and would thus affect N demand, according to the proposed definition of demand. At a later stage it may appear that some of the N-demand parameters are redundant.

The maximum N uptake rate u_N can reach values up to 0.8 g m^{-2} d^{-1}, as was observed in a young rice crop under very high (400 kg N ha^{-1}) N application at Aduthurai, India (Thiyagarajan et al., 1991; Ten Berge et al., 1994). This, however, is regarded as exceptional. At other locations, e.g. IRRI, Los Banos, Philippines, u_N remained below 0.5 g m^{-2} d^{-1}. It seems that, at least at IRRI, its value is lower for wet season than for dry season conditions. In any case, the value of u_N crucially affects biomass production according to model calculations.

A first estimate for q_N based on a number of experiments conducted within the framework of SARP is 0.035 g g^{-1}. Possibly, both u_N and q_N can reach higher values when the crop is highly deficient in nitrogen and is suddenly exposed to a large N supply. To determine u_N and q_N under such conditions, the crop must be sampled at short time intervals (e.g. 2 d).

The maximum overall (including roots) crop N content c_{max} usually starts at 0.04 kg kg^{-1} for very young plants, decreases then linearly to about 0.02 at flowering and 0.015 when the crop approaches maturity. These rather high values are typical of modern short duration varieties, and may be considerably lower in other rice types.

The remaining N-demand coefficient, $N_{L,max}$, may reach values up to 10 g per m^2 ground surface area, as observed at IRRI during 1993 dry season in rice cvar IR72 (Wopereis et al., this volume).

At any stage after exponential uptake, the minimum of potential uptake rates allowed by the limitations (1)-(5) is used in ORYZA_0 as the governing demand limitation.

Nitrogen uptake: soil N supply and fertilizer N recovery

The availability of N for uptake by the crop is determined by 'native' soil N supply, S_N (g N $m^{-2}d^{-1}$), applied amounts of N from mineral and/or organic fertlizer sources (g N m^{-2} d^{-1}), and $\rho_N(t)$ (g g^{-1}), the time course of apparent recovery of applied fertilizer-N. S_N represents the rate at which N released from mineralisation is taken up by the crop. It's value is estimated from N uptake in non-fertilized plots by dividing the full season's total N uptake by the number of field days. The resulting value ranges between 0.02 and 0.08 g $m^{-2}d^{-1}$, but for an average good rice soil S_N amounts to 0.05-0.06 g $m^{-2}d^{-1}$.

Fertilizer-N recovery reflects the competition for N between loss processes and uptake by roots. Because the size of the root system - and thus its competitive strength vs loss processes - increases rapidly during the vegetative stage, ρ_N first increases to reach a maximum around panicle initiation (PI) stage or later (up to flowering). Depending on environmental conditions and possibly also crop characteristics, the maximum ρ_N is sustained for a while and then usually declines soon after flowering. At some locations, e.g. at Sukamandi and Bogor, West Java, SARP teams have observed a steep decline of ρ_N already around the PI stage (see also Daradjat et al., this volume). This is currently attributed to soil conditions but certainly deserves further investigation. Whatever the explanation may be, the observed location specific $\rho_N(t)$ can be taken as a fact of life and must be taken into account in optimizing fertilizer management. It is, therefore, an input to the ORYZA_0 model. $\rho_N(t)$ can be obtained from field trials by evaluating the effects of N split applications given at different times (Ten Berge et al., 1994).

The model uses $\rho_N(t)$ as the best attainable recovery fraction, which thus defines the unavoidable fertilizer loss fraction. In reality, as in model calculations, the actual fertilizer-N recovery may be considerably lower than $\rho_N(t)$ if other uptake limitations exist. Hence, $\rho_N(t)$ can only be interpreted as a soil-cum-crop system characteristic when it is based on observations made under reasonable levels of N application. Fertilizer-N recovery observed under excessive N application has no significance as a system property. In ORYZA_0, $\rho_N(t)$ is applied on a day-to-day basis to convert, for a given day, a hypothetical amount of applied fertilizer to an amount potentially available for uptake. A first approximation of $\rho_N(t)$ for good rice soils shows a linear increase from 0.0 at transplanting to 0.4-0.7 at PI stage, increasing to 0.8-1.0 around FF stage, then again decreasing linearly to 0.0-0.2 over a time span of 3 weeks after FF.

Nitrogen uptake: the fertilizer application curve

The N application curve A(t) describes a hypothetical continuous, cumulative N application scheme. The slope dA/dt of this curve would represent the daily amount supplied, if it were possible to give fertilizer on a daily basis. The A(t) curve is presumed to be a member of the family of generalized logistic functions:

$$A(t) = c\,[1 + a\,e^{-b(t-m)}]^{-1/a} \qquad (9)$$

and its slope is given as the derivative

$$\frac{dA}{dt} = [\,b\,c\,(e^{-b(t-m)})\,(1 + a\,e^{-b(t-m)})\,]^{(-1-1/a)} \qquad (10)$$

where a and b are constants defining the shape of the curve, m the relative position of the curve with respect to the time axis, and c is the scale factor which defines the asymptote level approached at large t. As explained, the amount of N available for uptake from fertilizer equals $\rho_N(t)[dA/dt]$. The fraction not recovered, $(1-\rho_N)$, is not conserved for later uptake.

A(t) may remain well below the asymptote level during the whole season because the curve may be truncated: when A(t) reaches the user-prescribed total amount of fertilizer input, A_{tot} , the remainder of the logistic application curve is ignored. (This pattern can be seen in the optimization results for the lower A_{tot} values, as presented later in this paper.)

The cumulative application is, in ORYZA_0, not expressed directly as A(t) according to Eq. 9, but is obtained via integration of Eq. 10. This is necessary because another truncation occurs inherently at t = 0: the slope dA/dt and the function value A(t) are always positive and have a finite value. Thus, the cumulative application as given by Eq. 9 cannot be zero at the time of transplanting, although it should in reality, even irrespective of basal N application.

Verification of the biomass production relation; assessment of p

With a few exceptions, all parameters introduced in the previous paragraphs are straightforward coefficients which can be determined directly from experimental data. Their values represent, in fact, the model assumptions, and the accuracy of these values directly determines the prediction accuracy. Therefore, no attempts are made here to test the model as a whole, although error accumulation from uncertainties in inputs will have to be analyzed at a later stage. The biomass production component (Eqs 1-2) of the model, however, was subjected to a test to verify the usefulness of these new relations, and to obtain values for the parameters p, ε and α.

By adjusting p, ε and α by trial and error, predicted time series of total crop biomass were fitted to match the observed values, found in nine different experiments, covering several locations and rice varieties (Table 1). Most of these data are unpublished yet, but some of the experiments are described more extensively in this volume (Thiyagarajan et al.; Sivasamy et al.; Wopereis et al.). The two datasets collected in 1991 at IRRI were briefly discussed by Kropff et al., (1992). (The data collected at Jiangxi, and in 1991 (only) at IRRI include no root observations. Since the model predicts total biomass produced, the observed (shoot) biomass in these cases was augmented with an estimated value of root mass, based on an average root:shoot distribution pattern. This ratio was assumed (based on ten Berge, 1994) to decrease linearly from 0.40 at transplanting to 0.15 at flowering. No postflowering root growth was added.)

Each of the nine experimental datasets included a variable number of N management treatments, combining different total N input levels and timing of N application. R(t) and the measured values of $N_L(t)$ associated with the different treatments were used as forcing input functions. It was found that good fits can be obtained by maintaining the values of ε and α for all datasets at 3.5 g MJ^{-1} and 0.035 $m^2d^2MJ^{-1}$, respectively, while optimizing p per dataset. Figure 1 combines all available observed $W_c(t)$ and the associated predicted $W_c(t)$ values, for all experiments. It appears that for each dataset a single value of p can be found which coalesces all datapoints - different treatments and different sampling dates - closely to a regression line with slope 1:1. The resulting values of p are 11-12 g $g^{-1}d^{-1}$ for temperate hybrids, 11 g $g^{-1}d^{-1}$ for IR64, 8-9 g $g^{-1}d^{-1}$ for IR72, and 7 g $g^{-1}d^{-1}$ for the long duration cvar CR1009 and for the line IR58109-113-3-3-2. As a strong interdependence exists among the parameters p, α and ε, these p values are associated with the above mentioned values of α and ε. Comparisons with new independent datasets are required to verify whether p is indeed a stable varietal characteristic, yielding accurate biomass predictions with the help of Eqs 1-2 when combined with measured R(t) and $N_L(t)$, and fixed ε and α.

Table 1. Details of nine experiments used to validate the biomass production equations (Eqs. 1-2) and to determine the initial leaf nitrogen use coefficient, p. All datasets include time courses of leaf nitrogen amount N_L (see explanation in text), daily global radiation, and total crop biomass. In five cases, no root biomass was observed. For those sets, a correction has been made (see explanation in text).

Dataset	Location, Country	Month/Year of planting	Variety	Range of total N input (kg ha^{-1})	number of treatments	p (g g^{-1}d^{-1})	Range of observed biomass (t ha^{-1})	Range of observed grain yield (t ha^{-1})
a.	Jiangxi, China	April 1988	Hybrid V49	0 - 225	7	12	10.2 - 15.7 (ex. roots)	5.8 - 7.8
b.	Jiangxi, China	July 1988	Hybrid V64	0 - 225	9	12	8.3 - 13.2 (ex. roots)	5.6 - 7.2
c.	Jiangxi, China	April 1989	Hybrid V49	150	7	11	10.5 - 11.2 (ex. roots)	6.3 - 6.9
d.	Thanjavur, India	Sept. 1991	CR1009	0 - 250	9	7	10.6 - 19.0	4.7 - 8.1
e.	Thanjavur, India	July 1992	IR64	0 - 125	6	11	10.9 - 17.1	4.7 - 7.5
f.	Aduthurai, India	July 1992	IR64	0 - 200	9	11	7.6 - 10.2 (to F stage)	-
g.	Los Banos, Phil's	July 1991	IR58109-3-3-2	0 - 110	3	7	10.0 - 12.8 (ex. roots)	4.1 - 6.1
h.	Los Banos, Phil's	July 1991	IR72	0 - 110	3	9	7.6 - 11.5 (ex. roots)	3.9 - 5.3
i.	Los Banos, Phil's	Jan. 1993	IR72	0 - 400	16	8	8.3 - 18.2	4.8 - 10.1

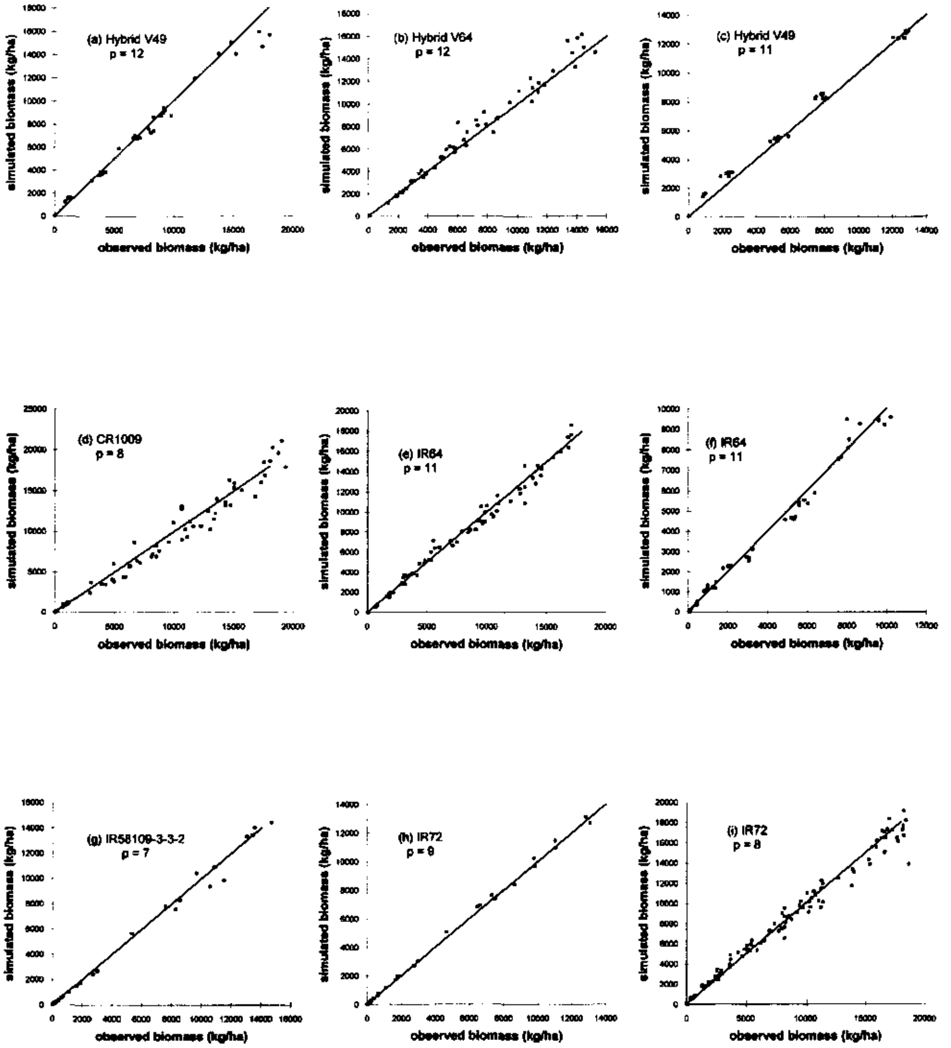

Figure 1. Observed vs predicted total crop biomass, for nine different experiments covering different locations, treatments and rice varieties. Details of each experiment are summarized in Table 1. Data points include all treatments and all sampling dates, which range from 20 DAT to maturity stage. Simulation results were obtained after assessment of the initial leaf nitrogen use coefficient, p, by calibration. The corresponding value is indicated in each graph. (a) Jiangxi, V49, (b) Jiangxi, V64, (c) Jiangxi, V49, (d) Thanjavur, CR1009, (e) Thanjavur, IR64, (f) Aduthurai, IR64, (g) Los Banos, line, (h) Los Banos, IR72, (i) Los Banos, IR72.

Determination of the fertilizer recommendation curve

Optimization procedure

Optimisation, generally, is searching the particular set of input parameter values which gives the closest approximation to some 'goal'. The goal here is the maximum attainable biomass production. Such exercise has a direct relevance to rice production only if the parameters to be found by optimization can indeed be directly influenced in the field. In the context of N management, the most 'manageable' variables are the form of fertilizer-N, the application technique, and the amount and timing of N application. We ignore the range of available N forms and application techniques, and assume all N application is in the form of broadcast prilled urea.

The concept of 'fertilizer recommendation curve' introduced here presumes that N application would ideally (from the crop's perspective) follow a continuous curve, which can be expressed by Eq. 9. Thus, we seek to find the optimum A(t) curve, i.e. those values of parameters a, b, c, and m leading to maximum biomass production under the specified external conditions and varietal characteristics. This optimum curve is defined as the fertilizer recommendation curve.

All factors other than A(t) are user defined constants and functions. They express varietal, soil, and weather characteristics, and have to be known. These factors remain constant in the optimization process. The validity of the resulting recommendation curve hinges on the validity of these inputs.

We applied the Price (1979) algorithm as documented by Stol et al., (1992) to identify the optimum values of a, b, c, and m. The Price algorithm is a global search procedure, which minimizes the risk of finding a local rather than global optimum. A number (e.g. 100) of parameter sets is defined, each set representing a combination of four values (a, b, c, m). These values may be randomly selected from the four input ranges corresponding to the parameters. The sets are contained in an initial pool, and the model ORYZA_0 is evaluated for each set. The resulting biomass values are stored in a pool, each with the corresponding parameter sets attached. Subsequently, a single new set (a, b, c, m) is generated with the help of a simplex formed from five elements randomly taken from this pool. This is repeated many times, each time feeding the new set into the model and evaluating the output. If the result is better (final biomass higher) than for the worst set (i.e., giving lowest biomass) contained in the pool, the new set (a, b, c, m) replaces this worst element. After a number of iterations, parameter values converge and when a preset stop criterion is reached, the best of parameter sets then available in the pool is considered the optimum.

Example: dry season recommendation curve for IRRI farm

As an example we present the results obtained by applying the above procedure to identify the fertilizer recommendation curve for variety IR72 on a Maahas Clay soil at the IRRI experimental farm, for dry season conditions.

All input parameters characterizing this particular production situation are listed in Table 2; the values chosen were either known from previous studies at this site, or derived or estimated from the results obtained by Wopereis et al., (this volume) in the 1993 dry season.

Table 2. Input parameters and functions used with ORYZA_0 to derive the N response curve and fertilizer recommendation curves depicted in Figures 2-5, for Los Banos dry season conditions, rice cvar IR72. TP: transplanting date; DAT: days after transplanting.

Crop parameters	Value	Unit	Soil parameters	Value	Unit
f_{NL}	0.55	$g\ g^{-1}$	S_N	0.06	$g\ m^{-2}\ d^{-1}$
r_N	0.20	$g\ g^{-1}\ d^{-1}$	ρ(t)	0.0 at TP 0.7 at 40 DAT 0.8 at 70-75 DAT 0.01 at 85 DAT linear interpolation	$g\ g^{-1}$
n_D	0.012	$g\ g^{-1}$			
q_N	0.035	$g\ g^{-1}\ d^{-1}$	Time parameters	Value	
u_N	0.5	$g\ m^{-2}\ d^{-1}$			
c_{max}	0.04 at TP 0.02 at 70 DAT 0.015 at 100 DAT linear interpolation	$g\ g^{-1}$	date of TP date of FF maturity	14 January 60 DAT 101 DAT	
$N_{L.max}$	10.0	$g\ m^{-2}$	N application parameters	optimized in range	Unit
p	8	$g\ g^{-1}\ d^{-1}$			
ε	3.5	$g\ MJ^{-1}$	a	0.9- 1.1	-
α	0.035	$m^2\ d\ MJ^{-1}$	b	0.0 - 0.5	d^{-1}
			c	10 - 500	$kg\ ha^{-1}$
			m	20 - 80	d
			A_{tot}	0 - 500	$kg\ ha^{-1}\ d^{-1}$

The optimization procedure was repeated for each of 10 N input levels, A_{tot}: 25, 50, 75, 100, 150, 200, 250, 300, 400 and 500 kg ha^{-1} (total N input). The 500 kg ha^{-1} level was included only to verify that indeed a plateau is reached at extreme input levels. A single model run yielded the biomass production for the 'control', 0 kg N ha^{-1}. Dry season weather data of 1991 were used. The resulting N response curve is given in Figure 2; it shows the highest attainable biomass for each of the selected N input levels. The response curve indeed shows a familiar pattern, and the absolute levels, too, are very realistic at first glance. Multiplication of these biomass values with a harvest index of 0.5, a value normally attained at IRRI during the dry season, leads to a grain yield of approximately 4 t ha^{-1} without fertilizer application; yield levels rise to 9-10 t ha^{-1} for N inputs beyond 200 kg N ha^{-1}.

The 9 fertilizer recommendation curves corresponding to the input levels indicated in Figure 2 (excluding 0 and 500 kg N/ha) are given in Figure 3. Two preliminary conclusions are drawn from this figure: (1) 70-80% of total N input should have been applied by ultimately 40 DAT, and (2) at low input levels, the best strategy is to apply almost all fertilizer only shortly before reaching 40 DAT. Both conclusions may very well be valid only under the particular set of conditions chosen in this example (Table 2).

The stage of panicle initiation is reached around 40 DAT, for this cultivar under IRRI dry season conditions. The recommendation curves thus confirm the general knowledge that N application at this stage boosts yields, but simultaneously raise doubts whether that is in any way related to the process of panicle initiation itself. The ORYZA_0 model ignores pre-flowering phenological development and Figure 3 just shows the N application strategy which maximizes the conversion of global radiation into biomass, under given conditions.

To evaluate the range of annual variations in the fertilizer recommendation curve arising from variations in global radiation level and pattern, optimum curves were calculated for IRRI dry season conditions using 15 years of observed weather data. Figures 4 and 5 summarize the results for total N input levels of 120 and 160 kg N ha^{-1}, respectively.

The five steps towards computer-based N fertilizer recommendation

In summary, the procedure proposed here to determine an optimum N management strategy, for a given soil and variety, and for a known radiation environment, consists of the following steps.

1. Determine all model input parameters; some of these are site specific, notably S_N and $\rho(t)$, but possibly some other parameters as well.
2. Run the optimization procedure to derive the N response curve (Figure 2).
3. Determine from this response curve which total N input level A_{tot} is best in view of economic, environmental, and other considerations.

4. Read the recommendation curve corresponding to the selected A_{tot} level (as exemplified in Figure 3).
5. Transform this curve into a discrete number of split dose applications, each of a specified size and at specified time, to arrive at a manageable practice.

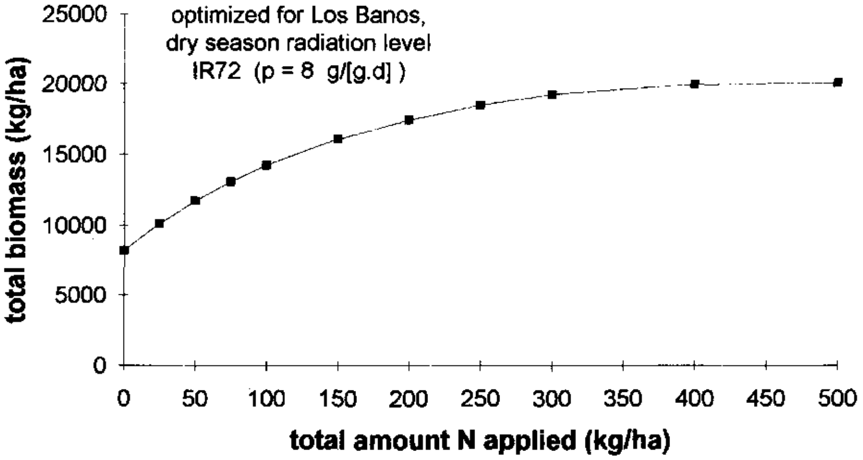

Figure 2. Maximum attainable total crop biomass production for cvar IR72 at selected total N input levels, for Los Banos dry season conditions, as predicted by the ORYZA_0 model. The curve was generated by optimization of the nitrogen application time curve for each of the N input levels.

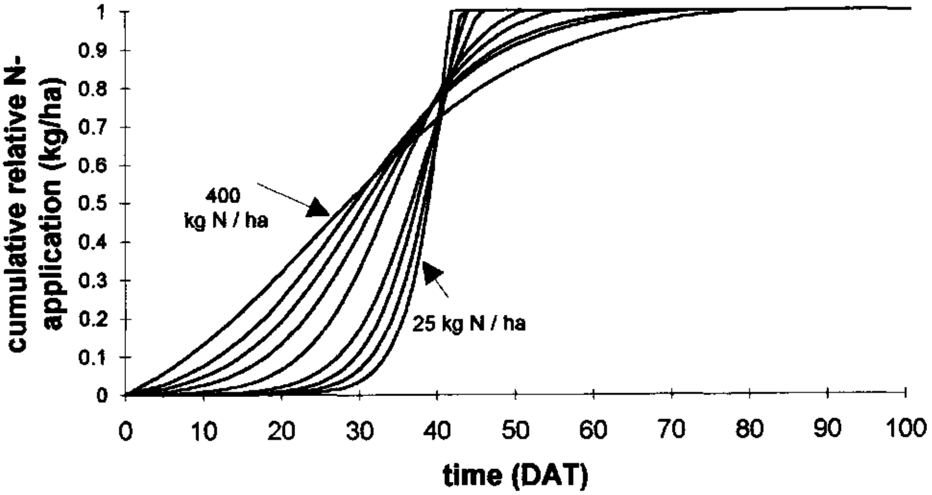

Figure 3. Nitrogen fertilizer recommendation curves corresponding to maximum biomass production for cvar IR72 and Los Banos dry season conditions. The curves were obtained by numerical optimization with the help of the ORYZA_0 model, and scaled relative to the total N input level: 25, 50, 75, 100, 150, 200, 250, 300, and 400 kg N ha^{-1}.

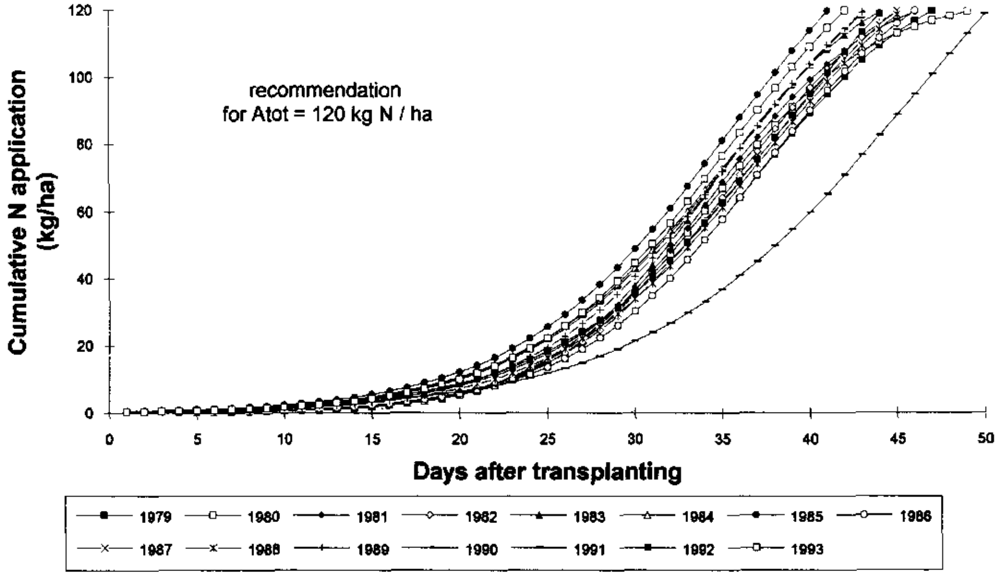

Figure 4. Effects of annual variability in dry season radiation pattern on the predicted nitrogen fertilizer recommendation curve for IR72 at a total input of 120 kg N ha^{-1}. The curves were obtained by numerical optimization to maximize biomass, with the help of the ORYZA_0 model.

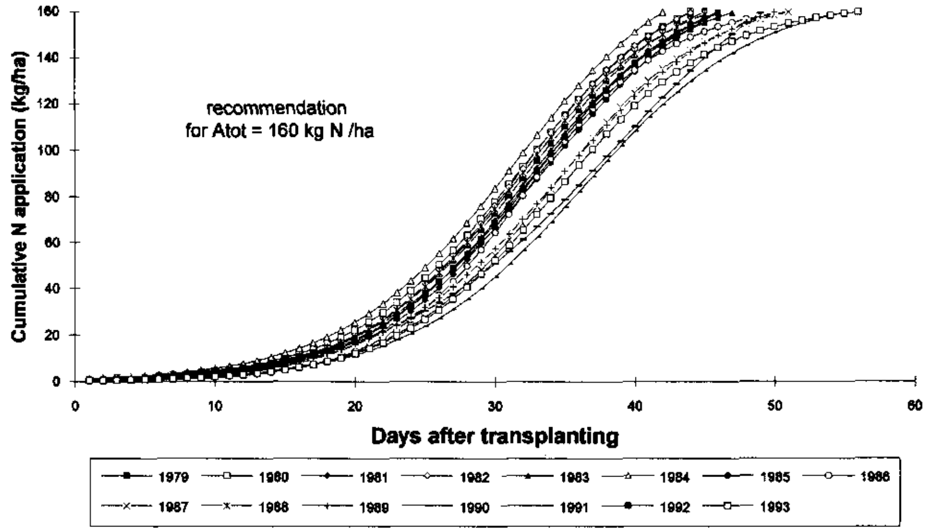

Figure 5. Effects of annual variability in dry season radiation pattern on the predicted nitrogen fertilizer recommendation curve for IR72 at a total input of 160 kg N ha^{-1}. The curves were obtained by numerical optimization to maximize biomass, with the help of the ORYZA_0 model.

This last transformation has not been discussed. The following procedure could be followed, but the issue requires further evaluation. Firstly, the continuous recommendation curve is segmented into time intervals, each of which is associated with one split dose application. The recommendation curve tells how much N must have been applied during that time segment by the time that interval is completed, and thus prescribes the size of the split dose. Applying this dose at the end of the corresponding time interval would leave the crop for too long without sufficient nitrogen supply: at time t, part of the recommended amount A(t) must have been absorbed by the crop already, according to the optimization calculations. Applying the dose at the start of the interval allows for more losses than necessary. As a first approximation, the split dose can be applied at the time when A(t) is halfway its total increment associated with the considered time interval, according to the recommendation curve.

Conclusions

Biomass accumulation in rice can be accurately calculated from global radiation and total canopy N content (g N m^{-2}) with the help of a simpel expression (Eq. 1) when the initial leaf nitrogen use coefficient p is known. In each of nine experimental datasets, biomass in all treatments and at all sampling dates was simulated well after assigning a single value to p for each whole experimental dataset. This value was obtained by curve fitting, and ranged from 7 to 12 g dry matter production per day, per g leaf nitrogen, at fixed (all datasets) values for the other two coefficients in Eqs. 1-2, ε and α. These value were 3.5 g MJ^{-1} and 0.035 m^2d MJ^{-1}, respectively.

Combination of the biomass production equation with a number of empirical soil and crop coefficients resulted in the simple model ORYZA_0. The fertilizer application curve A(t) is included in this model and can be optimized by numerical techniques, by optimizing the four parameters describing this generalized logistic function to maximize predicted biomass. Application of this technique to a case study for dry season conditions at the IRRI experimental farm resulted in an N response curve and fertilizer recommendation curves. These prescribe the optimal time course of fertilizer N application at selected total N input levels.

The N response curve appears to be realistic, matching the values commonly found at this site for unfertilized plots (8 t biomass ha^{-1}), and for high N applications (20 t biomass ha^{-1}). The entire curve has to be confirmed by independent experimental data from the same site. The recommendation curves indicate that roughly 75% of total N input must be given prior to 40 days after transplanting, and that application should be more condensed and nearer to this date when total N application is lower. As no information on the process of panicle initiation is taken into account by ORYZA_0, these results must be interpreted in relation to light interception and utilization only.

Considerable variation across years was found in the recommendation curves found by optimization for IRRI dry season conditions.

Future work

Verification trials

At the workshop reported in this volume of the SARP Research Proceedings it was concluded that the currently available information relevant to N management (see the many other contributions to this volume) should be compiled into a concise program, which can be applied to optimize N management under specific environmental conditions. The programs discussed here represent a first attempt and are available for the above purpose.

It was also agreed that we should now accept the challenge of testing such computer based recommendations against current recommended practice. Thus, verification experiments will be conducted in 1994 at a number of network sites, and treatments will include (1) the recommended practice ('standard' amount A_{tot} and 'standard' timing of N application), (2) the computer recommended timing, still maintaining the 'standard' A_{tot}, and (3) the computer recommended amount and timing. At IRRI, such verification trial is currently (dry season, 1994) under way, based on the very assessments presented above.

Research issues

One question to be addressed is: 'What penalty is paid for concentrating N application at discrete moments, instead of applying continuously?' For example, however small the early N requirement may be, omitting early application may result in delayed biomass development and consequently reduced N uptake later on. Such questions can be directly evaluated by models such as presented here.

Another topic for further study is the sensitivity of recommendation curves to the various input parameters. ORYZA_0 can also - when evaluated singly, i.e. without optimization - provide a framework for the identification of 'priority parameters', which merit further experimental study.

A full uncertainty analysis would also include an inquiry into the possible ranges covered by each of the input parameters. Within the context of SARP, the assessment of all relevant parameter values found at the different locations would be a logical activity for the immediate future. This will inform us about the existing ranges of the various parameters. Evaluating ORYZA_0, then, for the different available input parameter sets will increase our insights into the factors governing yield differences among the various network sites and cultivars.

Acknowledgements

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Evaluating Water Production Functions for Yield Assessment in Wheat Using Crop Simulation Models

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Abstract

A simulation study was conducted to test water production functions that relate biomass and grain yield to crop water use. The wheat growth model WTGROWS was used to predict biomass production and grain yield in New Delhi, India for 16 years of weather data for a range of irrigation treatments, varying from 60 mm - 350 mm per crop cycle. The simulated datasets of biomass production and yield were used to test 8 water production functions. Functions based on seasonal evapotranspiration and transpiration were rather site specific and did not reflect inter-seasonal weather variability. Predictions improved if information on vapor pressure deficit throughout the crop cycle was included. The yield reduction ratio for wheat, relating relative seasonal evapotranspiration deficit to relative yield deficit was 1.54. Use of production functions bases on division of the crop cycle in five growth stages improved the predictability of final biomass and grain yield. These functions can also be used to indicate the sensitivity of crop growth to soil moisture deficit at different growth phases.

Introduction

The production of grain or crop dry matter per unit water input is denoted as the water production function. It has been developed on the assumption that all production inputs other than water are non-limiting. The primary question involved in the development of these functions is the choice of independent variables, the dependent one being crop yield (Y) or final above ground biomass (TDM). Several workers (Jensen, 1968; Minhas et al., 1974; Stewart et al., 1977) used evapo-transpiration (ET) as independent variable while others (de Wit, 1958; Bierhuizen and Slatyer, 1965; Hanks, 1974) used transpiration (Tr) as the choice. The preference for Tr as an independent variable has been based on the fact that it has direct influence on plant growth, while ET has the advantage of ease of estimation. Some of the functions relate Y or TDM with seasonal ET or Tr as a linear or quadratic fit (Dillman, 1931). This form cannot explain differences in crop yields due to variability in evaporative demand of the atmosphere. This problem can be mitigated by relating crop yields with the ratio of ET (or Tr) to vapor pressure deficit (VPD), pan evaporation or potential evapo-transpiration (de Wit, 1958; Tanner and Sinclair, 1983). Stewart et al. (1977) introduced the yield reduction ratio, defined as the ratio of relative crop yield reduction to relative ET deficit. This index gives a measure of crop sensitivity to water stress. Doorenbos et al. (1979) used this approach for several crops to quantify the relationship between yield and water use.

There is ample evidence to suggest that the sensitivity of cereals to drought stress depends on the growth stages. To incorporate such dependency, inter-stage (or dated) production functions relating relative Y or TDM with inter-stage relative ET or Tr through linear multiple regression, additive type (Stewart et al., 1977) or non-linear multiple regression, multiplicative type (Jensen, 1968; Hanks, 1974; Minhas et al., 1974) have been developed. The regression coefficients corresponding to various growth stages then quantify the sensitivity of crop yield to drought stress in various stages. Normally the crop growth stages (number and duration) are chosen on the basis of days after sowing for computing relative ET or Tr. This may not be a sound approach as crop phenological development may not match in different years and differential profile moisture regime treatments. Field experiments conducted in different years for evaluating the growth response to variable moisture supply may not be suitable as a general basis for generating water production functions as in different years, the crop is subjected to different radiation and evaporative demands. In addition, information from long term experiments is available for few locations only. Moreover, the comparative performance of the various available production functions has not been simultaneously evaluated on a given set of experimental data.

Keeping these limitations in view, a preliminary study was undertaken to generate datasets required for assessing various production functions by having varying set of irrigation treatments covering the entire moisture availability range i.e., limited, moderate and adequate for 16 years weather during 1972 - 1973 to 1991 - 1992 using the model WTGROWS, Wheat Growth Simulator (Aggarwal et al., 1993), well validated for different agro-environments. As this database contains changes only in water availability with all other factors being non-limiting, simultaneous testing of existing water production functions may help identifying suitable production functions for given situations. Quantitative evaluation of the sensitivity of various crop growth stages to drought stress may also be possible. This can help in deciding allocation of irrigation water available for maximizing crop production. This might not be possible with real datasets, pooling several experiments over a number of years, because factors other than water may be limiting in reality.

Theory

Dillman (1931) developed water production function of the type

$$Y \text{ (or TDM)} = a + b * ET$$

where ET refers to the cumulative value of ET over the entire growing season and a and b are constants.

Tanner and Sinclair (1983) included averaged VPD over the growing season along with seasonal Tr for prediction of growth and subsequent yield

$$Y \text{ (or TDM)} = m * Tr / VPD$$

where m is a crop factor.

Bierhuizen and Slatyer (1965) took the ratio of cumulative transpiration, Tr_i to averaged VPD_i in different growth stages *i* and summed them up and related to final TDM and Y

$$Y \text{ (or TDM)} = a * \sum_i Tr_i / VPD_i + b$$

where a and b are constants and Σ denotes the summation of arguments.

Stewart et al. (1977) introduced relative seasonal evapo-transpiration deficit, RETD defined as $1 - ET / ET_m$ and related it to relative biomass production deficit, RTDMD defined as $1 - TDM / TDM_m$ and relative yield deficit, RYD defined as $1 - Y / Y_m$

$$RYD \text{ (or RTDMD)} = a * RETD + b$$

where ET_m, Y_m and TDM_m correspond to the seasonal ET, grain yield and total above ground biomass values under adequately irrigated condition and a and b are constants. The slope of the regression equation for grain yield is termed as yield reduction ratio. It is a measure of crop sensitivity to water stress. Doorenbos et al. (1979) used this function for several crops to quantify relationship between yield and water use.

Additive model for dependence of crop growth and subsequent yield on inter-stage moisture availability was developed by Stewart et al. (1977)

$$RYD \text{ (or RTDMD)} = \left(\sum_i A_i * RETD_i + B\right) / ET_m$$

where $RETD_i$ refers to the relative seasonal ET deficit for various crop growth stages represented by suffix, *i*. The values of regression coefficients for various growth stages, A_i are indicators of the sensitivity of the stages for water availability in deciding the subsequent yield and B in the equation is a regression constant.

Jensen (1968) introduced multiplicative inter-stage production function by taking relative seasonal evapo-transpiration, i.e. ET / ET_m, of various stages as independent variables for assessment of yield expressed through relative yield, Y / Y_m:

$$Y / Y_m = B * \prod_i (ET / ET_m)^{A_i}$$

The symbol Π denotes here the multiplication of arguments. Higher values of the regression coefficient A_i indicate a higher sensitivity of that stage towards water availability. The values thus can guide in scheduling of irrigation under variable water supply for getting maximum possible crop yields under optimal or sub-optimal schedules of irrigation.

Relative seasonal transpiration, i.e. Tr / Tr_m, of various stages were taken as independent variables by Hanks (1974) for prediction of grain yield expressed through relative yield:

$$Y / Y_m = B * \prod_i (Tr / Tr_m)^{A_i}$$

This approach is widely used in irrigation management programs. Predictability of crop yields to near reality as well quantification of sensitivity of moisture availability in various crop growth stages are the main features of this function, but the only limitation is that it involves transpiration computation which normally is a difficult task in field experimental studies.

Minhas et al. (1974) developed an economic production function taking relative evapo-transpiration in various crop growth stages for prediction of the grain yield:

$$Y / Y_m = B * \prod_i [\, 1 - (1 - ET / ET_m)^2]^{A_i}$$

where A_i refers to the sensitivity of stage i for moisture availability. The production functions stated above require simultaneous testing for their comparative performance in assessing total above ground biomass and grain yield.

Materials and Methods

Datasets required for evaluating various seasonal and inter-stage water production functions were obtained using WTGROWS, a wheat growth simulator (Aggarwal et al., 1993). Location for study was IARI Farm, N. Delhi, India situated at $28^o\,38'$ N and $70^o\,10'$ E and at an elevation of 228.6 m above the mean sea level. The soil characteristics were sandy loam with the volumetric moisture contents at field capacity, permanent wilting point and air dry state ranging from 23.9-15.4%, 6.7-7.8% and 5.0%, respectively. The profile moisture content at the time of sowing was initialized to about 80 per cent of the field capacity in 0-150 cm soil layer. 26 irrigation treatments covering entire range from limited to adequate water supply were used for running the model. The treatments primarily included sequencing of one to five irrigations of 60 mm each. Five of the treatments included one irrigation, six treatments included two irrigations, nine treatments included three irrigations, five treatments included four irrigations and one treatment included five irrigations. The latter was viewed as the potential yield treatment. The time of irrigation matched roughly with either one or more of the critical physiological stages such as crown root initiation, early and late vegetative phases, flower initiation and milk stage. Other inputs such as fertilizer were according to the standard optimum recommendations. Crop characteristics for high yielding, short duration and triple dwarf wheat were used in the model (Aggarwal et al., 1993). Sixteen years of weather data from 1972-1973 to 1991-1992 were used to generate a total of 416 data points for comparative evaluation of various production functions. For the inter-stage production functions, five stages of physiological development were identified as follows : first stage (0-0.24), second stage (0.24-0.52), third stage (0.52-0.75), fourth stage (0.75-1.0) and post flowering (1.0-2.0) (Keulen and Seligman, 1987). The model WTGROWS was executed to generate the values of the parameters such as ET, Tr, Y, TDM, VPD etc. required for evaluating various production functions.

Results and Discussion

The relationship of seasonal ET (mm) with TDM (kg/ha) and Y (kg/ha) is:

$$TDM = -7170.8 + 90.4 * ET - 0.097 * ET^2 \qquad r^2 = 0.734$$

$$Y = -4729.7 + 44.2 * ET - 0.046 * ET^2 \qquad r^2 = 0.549$$

The cumulative value of ET over the entire growing season accounted for only 55 per cent of variance in grain yield (Figure 1). The poor predictability of Y and TDM found for the pooled datasets must be ascribed to year to year weather variability. Applying this relationship to each year separately, increased r^2 dramatically as weather was the only year - specific input. Predictability improved by about 8 - 10 per cent when seasonal Tr instead of ET was used as independent variable to predict TDM and Y. The relationships obtained are:

$$TDM = - 3016 + 79.929 * Tr - 0.086 * Tr^2 \qquad r^2 = 0.841$$

$$Y = - 2492 + 36.79 * Tr - 0.034 * Tr^2 \qquad r^2 = 0.626$$

Subsequently we tested the water production function developed by Tanner and Sinclair (1983) and the results are plotted in Figures 2 and 3. By using this approach, the prediction of TDM and Y were improved to considerable extent. Similar relationships were tried by replacing Tr with ET, for the sake of convenience as evapo-transpiration is an easily determinable parameter when compared with transpiration. But this reduced the r^2 value as expected:

$$\mathrm{TDM} = 43.553 * \mathrm{ET} / \mathrm{VPD} + 688 \qquad r^2 = 0.865$$

$$\mathrm{Y} = 23.534 * \mathrm{ET} / \mathrm{VPD} + 2012 \qquad r^2 = 0.740$$

Seasonal Tr based functions performed better than seasonal ET based functions because Tr is the directly related to crop activity.

The ratios of Tr to VPD in five growth stages were summed up and related to TDM and Y (Bierhuizen and Slatyer, 1965). This could not further improve the predictive performance of the production function:

$$\mathrm{TDM} = 48.358 * \sum_i \mathrm{Tr}_i / \mathrm{VPD}_i + 201 \qquad r^2 = 0.922$$

$$\mathrm{Y} = 25.567 * \sum_i \mathrm{Tr}_i / \mathrm{VPD}_i + 1622 \qquad r^2 = 0.757$$

where suffix i represents the crop growth stage and can have value from 1 to 5.

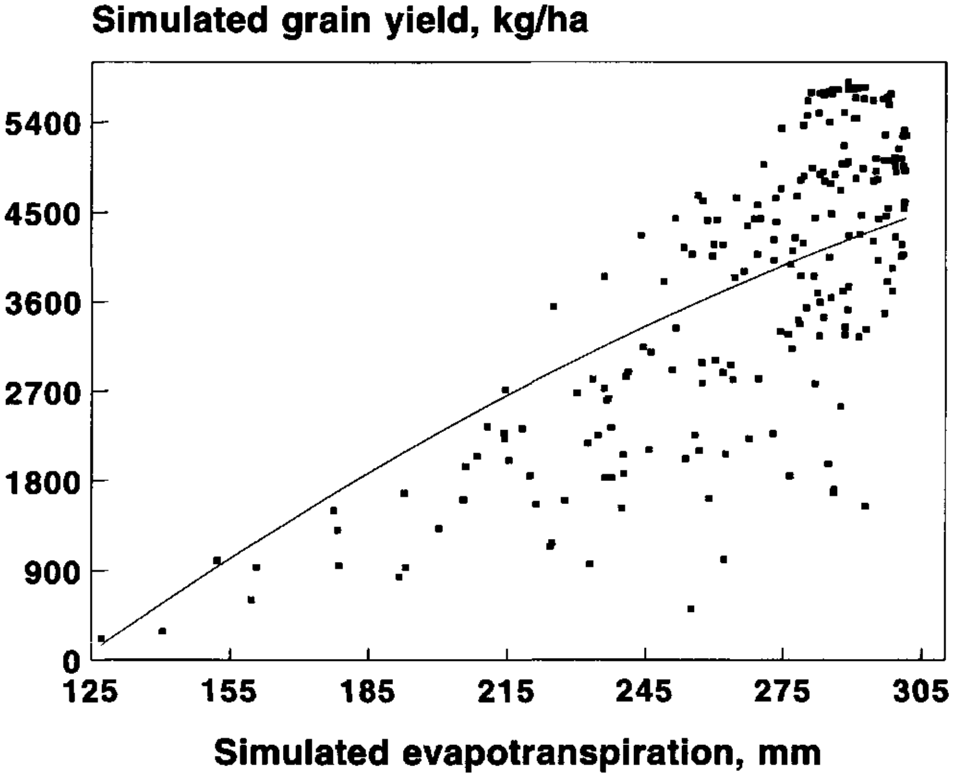

Figure 1. Relationship of seasonal evapo-transpiration with grain yield of wheat.

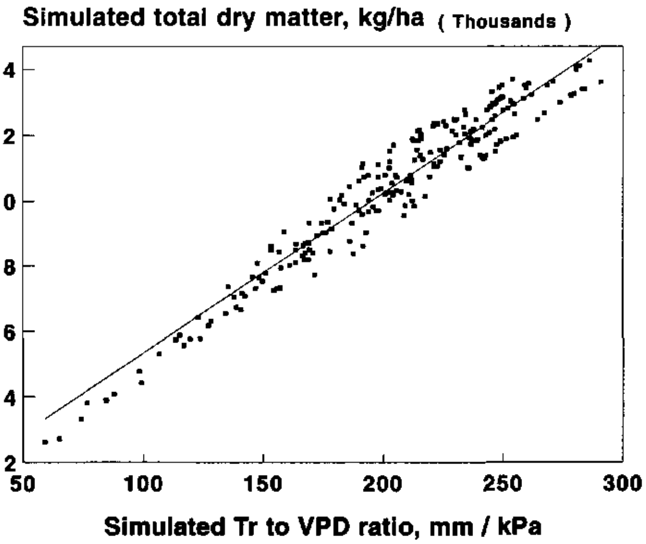

Figure 2. Relationship of ratio of seasonal transpiration to averaged vapor pressure deficit with final above ground biomass of wheat.

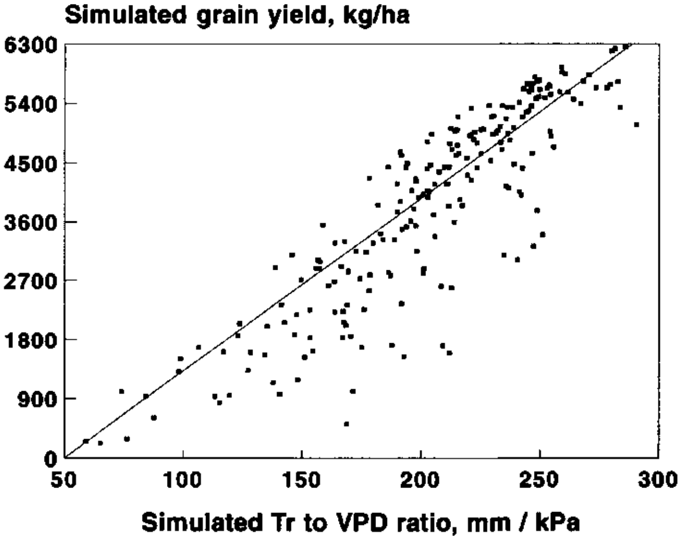

Figure 3. Relationship of ratio of seasonal transpiration to averaged vapor pressure deficit with grain yield of wheat.

Relative evapotranspiration deficit, RETD was related to relative biomass production deficit, RTDMD and relative yield deficit, RYD and the results are shown in Figures 4 and 5. Predictability could improve to 96 and 92 per cent for estimating total biomass and grain yield, respectively. This function has been widely used in assessing final growth and yield for various crops. The yield reduction ratio was found out to be 1.54.

Relative transpiration deficit, RTrD defined as 1 - Tr/Tr_m, when related with RTDMD and RYD gave the following results:

$$\mathrm{RTDMD} = 0.9984 * \mathrm{RTrD} - 0.0046 \qquad r^2 = 0.99$$

$$\mathrm{RYD} = 1.2986 * \mathrm{RTrD} - 0.0128 \qquad r^2 = 0.961$$

Additive function given by Stewart et al. (1977) was tested and the regression coefficients for different stages are given below:

$$\mathrm{RTDMD} = \left(\sum_i A_i * \mathrm{RETD}_i - 3.9916 \right) / \mathrm{ET_m} \qquad r^2 = 0.984$$

where $A_1 = -109$, $A_2 = 79$, $A_3 = 98$, $A_4 = 133$ and $A_5 = 154$.

$$\mathrm{RYD} = \left(\sum_i A_i * \mathrm{RETD}_i - 0.8523 \right) / \mathrm{ET_m} \qquad r^2 = 0.956$$

where $A_1 = -274$, $A_2 = 54$, $A_3 = 27$, $A_4 = 57$ and $A_5 = 350$.

The predictability improved slightly over the previous seasonal relative ET deficit function. The value of the regression coefficient during post anthesis phase was very high indicating the importance of moisture availability in that stage for ensuring higher grain yields. Similar type of equations were tried for relative transpiration deficits:

$$\mathrm{RTDMD} = \left(\prod_i A_i * \mathrm{RTrD}_i - 4.24 \right) / \mathrm{Tr_m} \qquad r^2 = 0.99$$

where $A_1 = -1.2$, $A_2 = 31$, $A_3 = 56$, $A_4 = 104$ and $A_5 = 132$.

$$\mathrm{RYD} = \left(\prod_i A_i * \mathrm{RTrD}_i - 8.274 \right) / \mathrm{Tr_m} \qquad r^2 = 0.966$$

where $A_1 = 9$, $A_2 = 36$, $A_3 = -31$, $A_4 = 41$ and $A_5 = 296$.

The multiplicative inter-stage production function given by Jensen (1968) was evaluated for assessing TDM and Y:

$$\mathrm{TDM} / \mathrm{TDM_m} = 0.986 * \prod_i (\mathrm{ET} / \mathrm{ET_m})^{A_i} \qquad r^2 = 0.963$$

where $A_1 = -0.34$, $A_2 = 0.15$, $A_3 = 0.31$, $A_4 = 0.52$ and $A_5 = 0.27$.

$$\mathrm{Y} / \mathrm{Y_m} = 0.997 * \prod_i (\mathrm{ET} / \mathrm{ET_m})^{A_i} \qquad r^2 = 0.973$$

where $A_1 = -0.85$, $A_2 = 0.1$, $A_3 = 0.035$, $A_4 = 0.479$ and $A_5 = 0.952$.

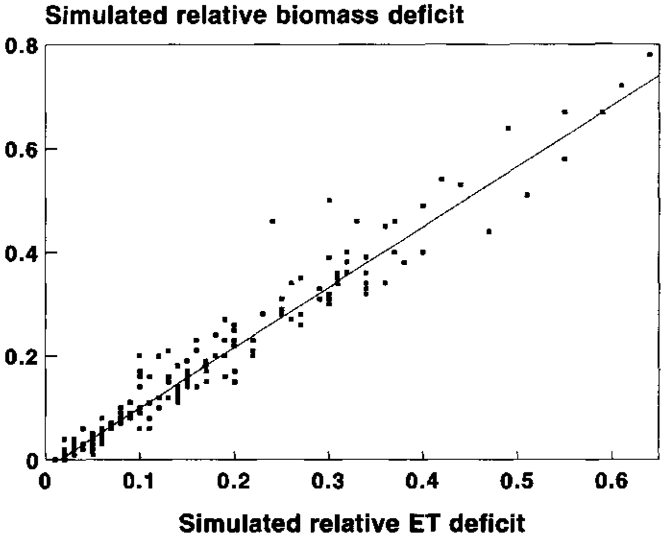

Figure 4. Relationship of relative seasonal evapo-transpiration deficit with relative final above ground biomass deficit of wheat.

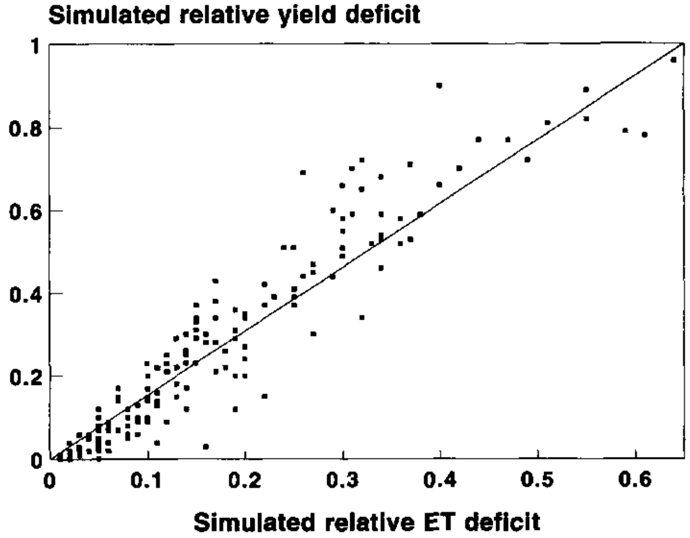

Figure 5. Relationship of relative seasonal evapo-transpiration deficit with relative grain yield deficit of wheat.

When relative seasonal transpiration of various stages were taken as independent variables (Hanks, 1974), the following relationships were obtained:

$$TDM / TDM_m = 0.983 * \prod_i (Tr / Tr_m)^{A_i} \qquad r^2 = 0.975$$

with $A_1 = -0.027$, $A_2 = 0.023$, $A_3 = 0.245$, $A_4 = 0.358$ and $A_5 = 0.279$.

$$Y / Y_m = 1.008 * \prod_i (Tr / Tr_m)^{A_i} \qquad r^2 = 0.979$$

with $A_1 = 0.05$, $A_2 = 0.04$, $A_3 = -0.13$, $A_4 = 0.155$ and $A_5 = 0.933$.

The production functions of Jensen (1968) and Hanks (1974) also indicated the sensitivity of moisture availability during post anthesis duration. Figure 6 shows the comparison between relative biomass, simulated verses estimated from equations developed from either Hanks or Jensen approaches. Hanks approach seemed to perform slightly better. Similarly when relative yield was plotted (Figure 7), the difference between simulated from WTGROWS and estimated from these two approaches narrowed down in both the approaches.

Economic production function of Minhas et al. (1974) when tested with the given datasets could not improve the predictability further when compared with Hanks approach. The equations generated for predicting relative biomass and yield on the basis of inter-stage relative ET values are given as:

$$TDM / TDM_m = 0.913 * \prod_i [1 - (1 - ET / ET_m)^2]^{A_i} \qquad r^2 = 0.91$$

where $A_1 = -4.17$, $A_2 = 0.33$, $A_3 = 0.59$, $A_4 = 0.99$ and $A_5 = 0.42$.

$$Y / Y_m = 0.876 * \prod_i [1 - (1 - ET / ET_m)^2]^{A_i} \qquad r^2 = 0.923$$

where $A_1 = -12$, $A_2 = 0.224$, $A_3 = 0.128$, $A_4 = 0.651$ and $A_5 = 1.489$.

When relative ET values were replaced by relative Tr values, the degree of predictability of yields could improve to a little extent:

$$TDM / TDM_m = 0.918 * \prod_i [1 - (1 - Tr / Tr_m)^2]^{A_i} \qquad r^2 = 0.927$$

where $A_1 = 0.079$, $A_2 = 0.099$, $A_3 = 0.506$, $A_4 = 0.582$ and $A_5 = 0.396$.

$$Y / Y_m = 0.885 * \prod_i [1 - (1 - Tr / Tr_m)^2]^{A_i} \qquad r^2 = 0.927$$

where $A_1 = -0.009$, $A_2 = 0.082$, $A_3 = -0.14$, $A_4 = 0.089$ and $A_5 = 1.332$.

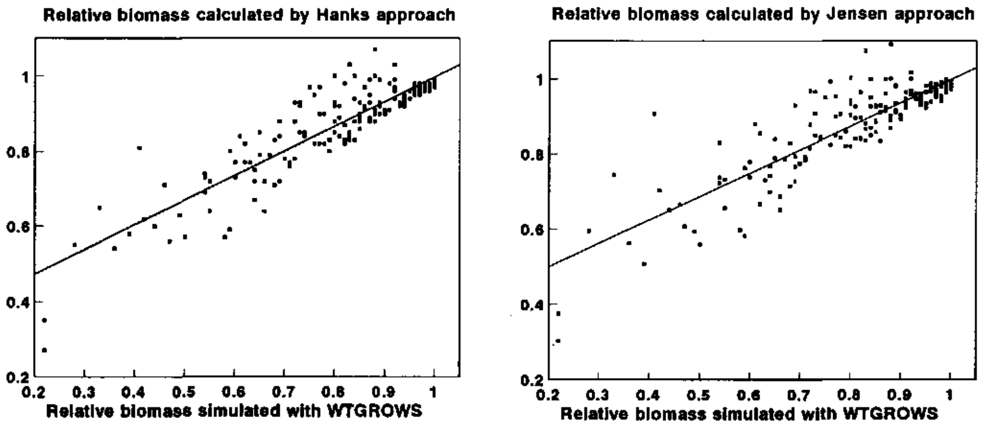

Figure 6. Comparison of relative biomass of wheat, simulated versus calculated by the Hanks and the Jensen approach, respectively.

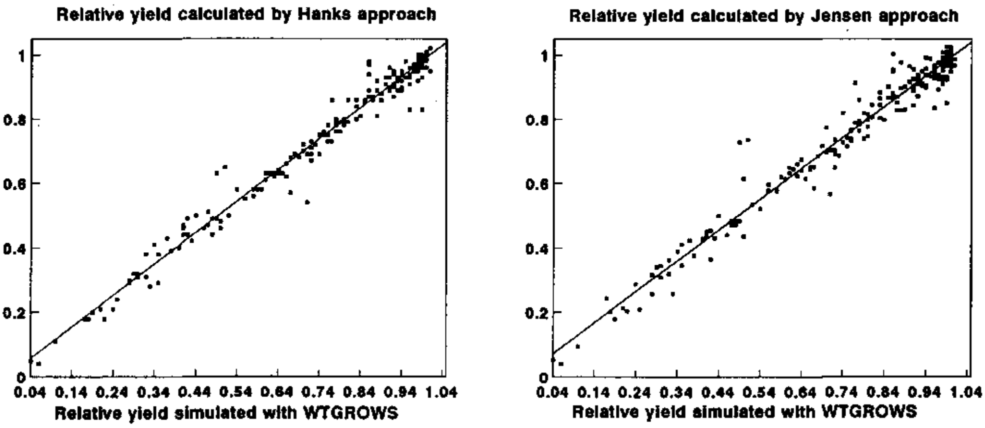

Figure 7. Comparison of relative grain yield of wheat, simulated versus calculated by the Hanks and the Jensen approach, respectively.

There is a need to develop a relationship between applied water in various stages, APW_i (precipitation plus irrigation, mm) with yield and final biomass, which can thus be conveniently used by planners as well as water management engineers for decision making over large command areas. Linear multiple regression analysis carried out in this regard gave the following results:

$$TDM = 43.1 * APW_1 + 28.0 * APW_2 + 17.6 * APW_3 + 14.1 * APW_4 + + 3.8 * APW_5 + 6226 \qquad r^2 = 0.923$$

$$Y = 17.7 * APW_1 + 15.7 * APW_2 + 13.9 * APW_3 + 13.0 * APW_4 + + 3.9 * APW_5 + 1383 \qquad r^2 = 0.927$$

Stages 1-5 in this function were as follows: first stage (0-0.52), second stage (0.52-0.75), third stage (0.75-1.0), fourth stage (1.0-1.5) and fifth stage (1.5-2.0). This change was done to analyze the criticality of water applied after milk formation stage. This kind of function though performed better but would lack of being site specific in nature.

Summary and Conclusion

Datasets generated with the help of System Analysis using WTGROWS (Wheat Growth Simulator) were used to compare the existing water production functions. Seasonal ET and Tr based functions could not answer inter-seasonal weather variability and also seemed to be site specific in nature. When vapor pressure deficit was incorporated in seasonal ET or Tr, the predictability improved considerably. The yield reduction ratio for wheat was 1.54. Production functions using inter-stage crop water use values improved the predictability further and could quantify the sensitivity of various stages towards moisture availability for deciding the ultimate crop yield. Hanks formulation of inter-stage relative transpiration for yield assessment performed the best. This paper revealed the potential of generating datasets by System Analysis Approach for these kind of studies, which thus can effectively help in the process of decision making. This preliminary study can further be extended to include water - nitrogen interactions, and can be applied to develop production functions for many different agro-climatic conditions.

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Time courses of leaf nitrogen concentration required to attain target yields in transplanted rice.

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Abstract
Five field experiments with three rice cultivars and different N application strategies were conducted under irrigated lowland conditions. The N concentration in the green leaves was highest during the tillering stage, reaching a maximum of 45.1 g kg^{-1}. Grain yields ranged from 2.2 to 8.2 Mg ha^{-1}. A Time Course of Sufficient Leaf Nitrogen Concentration (TCSLNC) with four significant parts is proposed for achieving yields of 8 Mg ha^{-1}. Observed yields below 8 Mg ha-1 were always associated with leaf N concentrations lower than TCSLNC during any part of the growth period. Leaf N concentration should be above TCSLNC curve for yields higher than 8 Mg ha^{-1}. For 10 Mg yield, the leaf N concentration should be substantially higher from tillering to flowering, than dictated by the TCSLNC derived for a 8 Mg ha^{-1} target yield.

Introduction

Rice grain yield is the integrated outcome of interactions of environment and management on a cultivar. Once the location and cultivar are chosen for transplanted rice cultivation, the farmer has little influence on the weather and the varietal potential. Eventually, the management factor becomes crucial in determining the yield. Rice crop management is very complex, involving several elements ranging from soil to the social conditions of the farmer. However, we can single out N management for its spectacular impact on grain yield. Leaf growth, biomass accumulation and seed growth are all altered very much by variations in nitrogen supply and the effect is much more than that of any other mineral nutrient. This is essentially because the N concentration in leaves is highly correlated with the concentration of the CO_2 fixing enzyme in photosynthesis, ribulose 1,5 - biphosphate carboxylase / oxygenase (Greenwood et al., 1991), and hence the potential maximum rate of photosynthesis would be linearly related to the nitrogen concentration in the leaf (Black, 1993). Besides, N is an essential constituent of chlorophyll. It has also been reported (Sinclair, 1990) that the radiation use efficiency for CO_2 assimilation depends upon the N concentration in the leaves and new leaf area is developed only when there is enough nitrogen. Also, during the seed growth, N is translocated to the grains, mostly from the leaves.

Thus, the basic composition of leaves requires a minimum N concentration to function actively, and the concentration has to be elevated to produce higher yields. The numbers of tillers and spikelets are closely associated with the N content of the plant during the growth periods corresponding to the formation of these yield components (Matsushima, 1976). Crop N uptake is the outcome of a crop's inherent requirements combined with N supply and other environmental conditions. The concentrations of a given nutrient in different plant parts are related to each other and to the concentration in the entire plant (Black, 1993). Several reports are available on the critical concentrations of N in rice. They are related to specific growth stages of the crop; e.g. panicle initiation (Takashaki, 1965; Tanaka & Yoshida, 1970; Brandon & Wells, 1986). The concentration of N in leaves fluctuates with time after planting, depending upon the physiological stage and N supply (Matsushima, 1976; Marschner, 1986). It can be assumed that a minimum concentration of N in the leaves is essential to attain a given yield level. When the supply is sub-optimal, growth is retarded; and N is mobilized from mature leaves for translocation to areas of new growth, thus enhancing the senescence of older leaves (Marschner, 1986).

In this paper, an attempt is made to define a time course of nitrogen concentration in rice leaves which is sufficient to reach a yield goal of 8 Mg ha^{-1} and above. The analysis is based on experimental work conducted at two sites in Tamil Nadu, India, and at the International Rice Research Institute, Los Baños, Philippines.

Basic concepts and assumptions

1. A yield level of 8 Mg ha^{-1} is used as a reference, corresponding roughly to the highest yields observed in the Aduthurai and Thanjavur experiments (8.1 and 8.2 Mg ha^{-1} under highest N input).
2. The following physiological development stages are taken into account: initial tillering (IT), active tillering (AT), maximum tillering (MT), panicle initiation (PI), flowering (F) and harvest/maturity (M). Moreover, a stage exactly in between panicle initiation and flowering is recognized as important, because N uptake and leaf biomass often reach peak values at this mid heading (MH) stage. Exactly in between flowering and maturity the mid maturity (MM) stage is defined .
3. Leaf N concentration refers, in this study, always to green leaves only.
4. The entire green leaf mass is considered and no distinction is made between leaves of different age classes.
5. It is assumed that the crop has adequate supply of other nutrients and is free from pests and diseases.

Materials and methods

The data used for this study were obtained from five field experiments (Table 1) conducted at the Tamil Nadu Rice Research Institute (TNRRI), Aduthurai, India, and the Soil and Water Management Research Institute (SWMRI), Thanjavur, India. For validation of the results, the data from IRRI (Kropff et al., 1992) were used. All experiments included treatments of different N application levels ranging from 0 to 400 Kg ha^{-1}, with application time ranging from planting to flowering. In two of the experiments, organic sources of N were included.

Treatment details are given in Table 1. Some of the experiments have been described elsewhere (Thiyagarajan et al., 1991; Thiyagarajan et al., 1994; Sivasamy et al., 1994). In all experiments, plant samples were collected at different stages of the crop from planting to harvest, and biomass and N content of roots, leaves, stems and panicles were determined. Final grain yields (14 % moisture) were also recorded.

Results and discussion

The N concentrations in the leaves (n_L) as observed in Experiments 1-5 are listed in Table 2. In Experiment 1, n_L did not surpass 41.4 g kg^{-1}, although the quantity of N applied was up to 400 kg ha^{-1}. The highest n_L was always observed during the tillering stage. Minimum values were found around harvest stage. Up to flowering, n_L remained within a fairly narrow range, irrespective of N supply. Differences between treatments were usually within 10 g kg^{-1}, except in Experiment 1 which may be due to the very high levels of N applied. Although n_L increased to some extent as a result of N application, the main effect of N application was an increased production of leaves during the vegetative phase. This effect was clearest before panicle initiation. Afterwards, n_L declines rapidly if N supply is limited.

Table 1. Details of five experiments conducted in Tamil Nadu, 1988-1992.

Particulars	Expt. 1	Expt. 2	Expt.3	Expt.4	Expt.5
Location	Aduthurai	Aduthurai	Thanjavur	Aduthurai	Thanjavur
Period	Dec. - Mar. 1988 - 89	Sep.- Jan. 1991-92	Sep.- Jan. 1991-92	Jul.- Oct. 1992	Jul.- Oct. 1992
Variety	ADT 39	CR 1009	CR 1009	IR 64	IR 64
N applied (kg/ha)	0, 100, 200, 300, 400	0, 50, 100, 150, 200, 250	0, 50, 100, 150, 200, 250	0, 125, 200	0, 125
Crop duration (days)	89- 97	127	121	100	93

Table 2. Ranges of N concentration in the green leaves (unless otherwise stated) and grain yields obtained in the different experiments.

Growth stage	Expt. 1	Expt. 2	Expt.3	Expt.4	Expt.5
			N concentrations in the leaves (g kg^{-1})		
Planting	31.5	20.2	21.4	22.4	17.1
Active tillering	20.0 - 41.4	30.3 - 38.2	35.3 - 45.1	35.3 - 43.3	28.1 - 34.3
Panicle initiation	20.7 - 33.8	14.2 - 14.9	17.1 - 23.4	26.0 - 33.2	15.2 - 24.6
Flowering	09.7 - 27.2^{a}	09.4 - 18.0^{a}	15.8 - 25.2	12.9 - 22.5	12.9 - 21.8
Harvest	07.0 - 09.8^{a}	05.8 - 07.9^{a}	00.0^{b}- 13.0	NA	07.8 - 11.6
			Grain yield (t ha^{-1})		
	2.3 - 4.7	4.4 - 7.0	4.7 - 8.2	4.3 - 6.6	4.7 - 7.5

The Time Course of Sufficient Leaf Nitrogen Concentration (TCSLNC)

The highest yields recorded in the field experiments at Aduthurai and Thanjavur were 8.1 and 8.2 Mg ha^{-1}, recorded in Treatments T8 and T9 of Experiment 3, respectively. In T8, the N application strategy was to supply 150 kg N at 10 DAT and 100 kg N at PI; in T9, 150 kg N was applied in 6 equal splits at basal, 10 DAT, AT, MT, PI and F stages. The yield level of 8 Mg ha^{-1}, and $n_L(t)$, the corresponding course of nL over time t found in these two treatments, are used as references. A mean $n_L(t)$ was obtained as the average of the $n_L(t)$ curves found for Treatments T8 and T9 (Table 3). This mean $n_L(t)$ will be referred to as the Time Course of Sufficient Leaf N Concentration (TCSLNC). The curve is depicted in Figure.1. We interpret this curve as the leaf nitrogen concentration required to achieve a yield of 8 Mg ha^{-1}. Thus, the acronym TCSLNC in this paper refers always this particular target yield level.

It may be argued that the n_L is only a 'concentration' variable and that, actually, the total amount of N present in leaves should be considered. It seems, however, that the two are closely linked, within a given development phase. The number of tillers (Matsushima, 1976), leaves (Sinclair, 1990) and spikelets (Matsushima, 1976), and the and kernel weights (Matsushima, 1976) all increase with nL, as do radiation use efficiency (Sinclair & Horie, 1989) and photosynthetic activity (Yoshida, 1981).

For a number of example cases, it is shown that grain yields below 8 Mg ha^{-1} were always associated with nL dropping below the TCSLNC curve during at least some part of the growth period (Figures 2a-2g). The corresponding treatment details are given in Table 4.

An increase in n_L is generally associated with an increasing leaf numbers, reflecting the formation of new tillers. This holds also for N applied at the PI stage, although tillers initiated at PI may not become productive (Thiyagarajan et al., 1994). The net effect of N applied at this stage is to sustain tillers already existing, which would otherwise be resorbed.

Table 3. N concentration in the green leaves in the treatments for which the grain yield was 8 t ha^{-1} and the mean N concentration value interpreted as the Time Course of Sufficient Leaf Nitrogen Concentration (TCSLNC).

Growth stage	DAT	N concentration (g kg^{-1}) Treatment number in Experiment 3 T 8	T 9	Minimum (TCSLNC)
Planting	0	21.4	21.4	21.4
Early tillering	10	40.0	41.1	40.0
Active tillering	24	44.9	38.6	38.6
Max. tillering	43	15.9	22.8	15.9
Panicle initiation	59	18.3	23.4	18.3
Mid-heading	75	23.6	23.7	23.6
Flowering	91	23.6	23.7	23.6
Harvest	121	10.4	11.0	10.4

T 8: 150 kg N applied at 10 DAT and 100 kg N applied at panicle initiation. (Grain yield 8.1 t ha^{-1}); T 9: 150 kg N applied in 6 equal splits at, planting, 10 DAT, active tillering, maximum tillering, panicle initiation and flowering. (Grain yield 8.2 t ha^{-1})

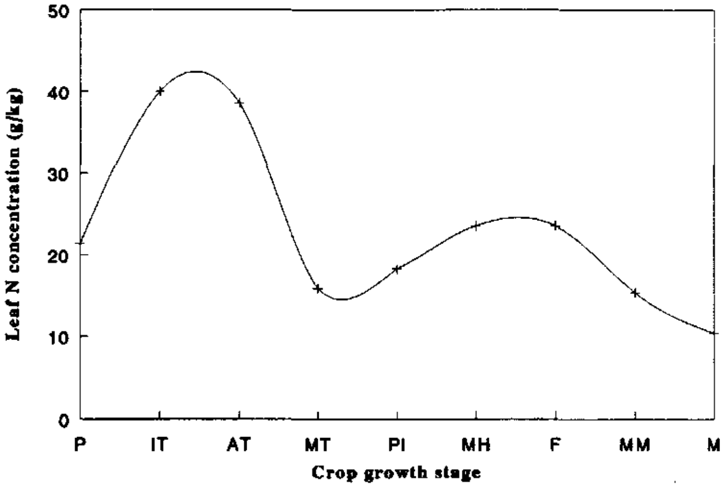

Figure 1. Time Course of Sufficient Leaf Nitrogen Concentration (TCSLNC) in transplanted rice for a grain yield target of 8 Mg ha^{-1}. The curve was derived from observed leaf nitrogen contents observed in Treatments T8 and T9 of Experiment 3, Thanjavur, 1991-92. For treatment details see Table 1.

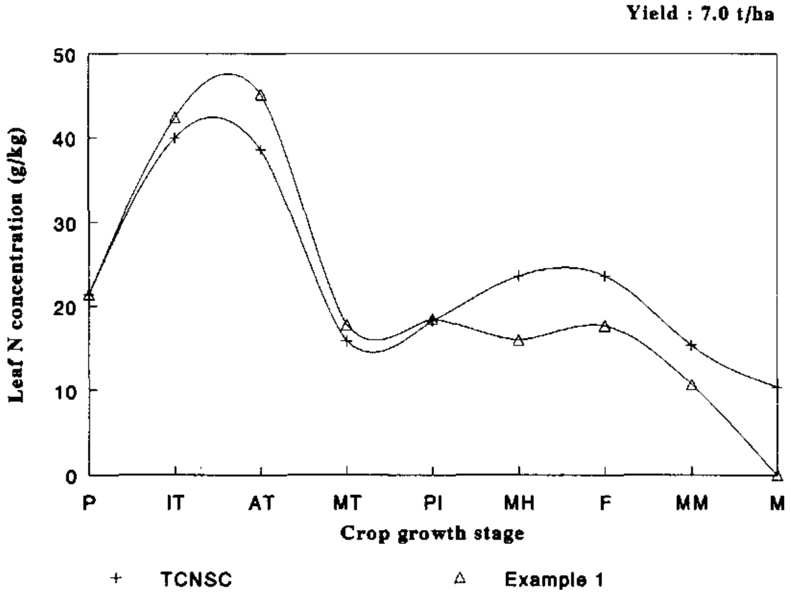

Figure 2a. Example 1 of $n_L(t)$ associated with a grain yield lower than 8 Mg ha^{-1}. Treatment details are given in Table 4.

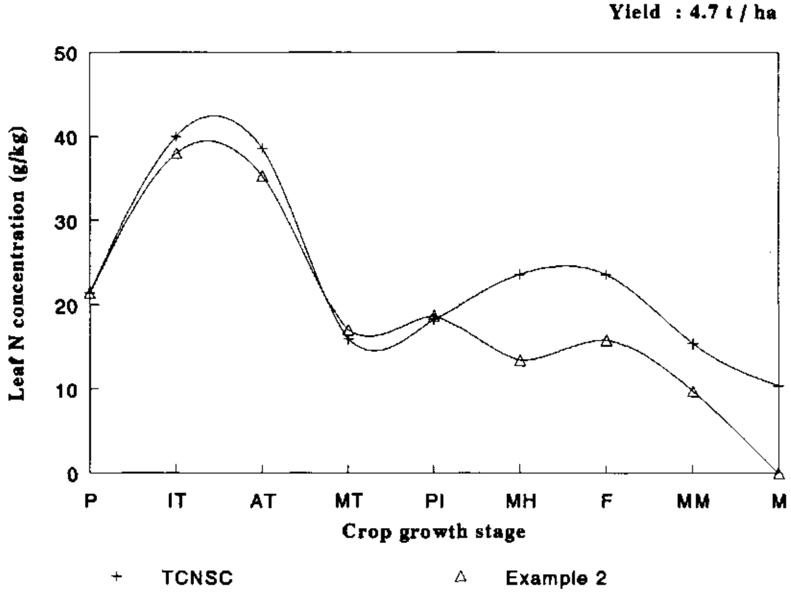

Figure 2b. Example 2 of $n_L(t)$ associated with a grain yield lower than 8 Mg ha^{-1}. Treatment details are given in Table 4.

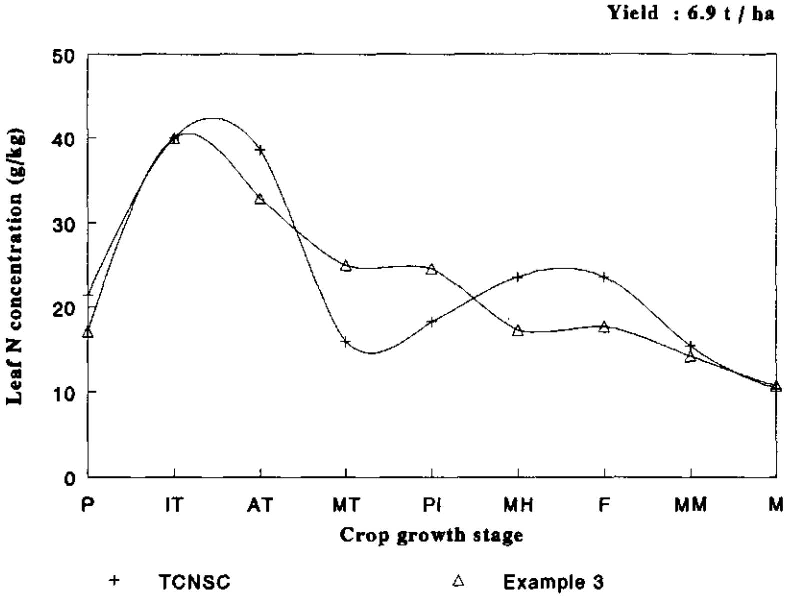

Figure 2c. Example 3 of $n_L(t)$ associated with a grain yield lower than 8 Mg ha^{-1}. Treatment details are given in Table 4.

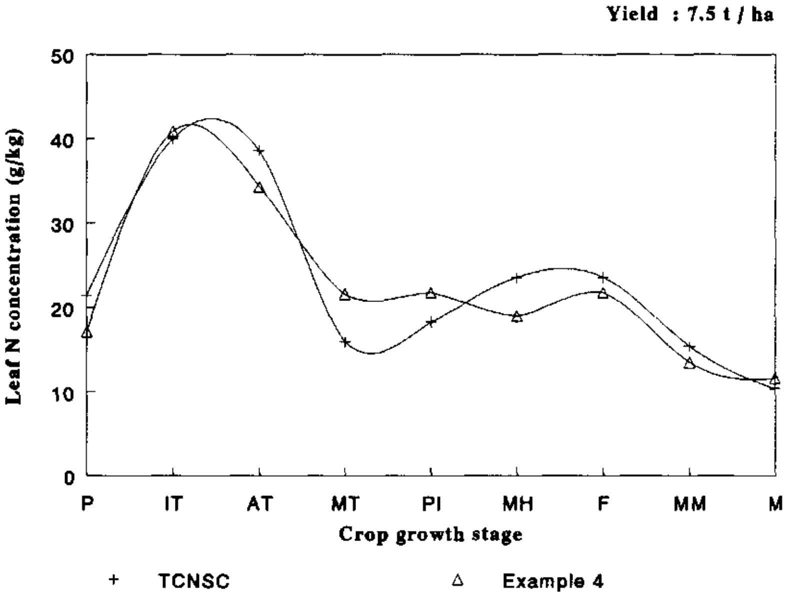

Figure 2d. Example 4 of $n_L(t)$ associated with a grain yield lower than 8 Mg ha^{-1}. Treatment details are given in Table 4.

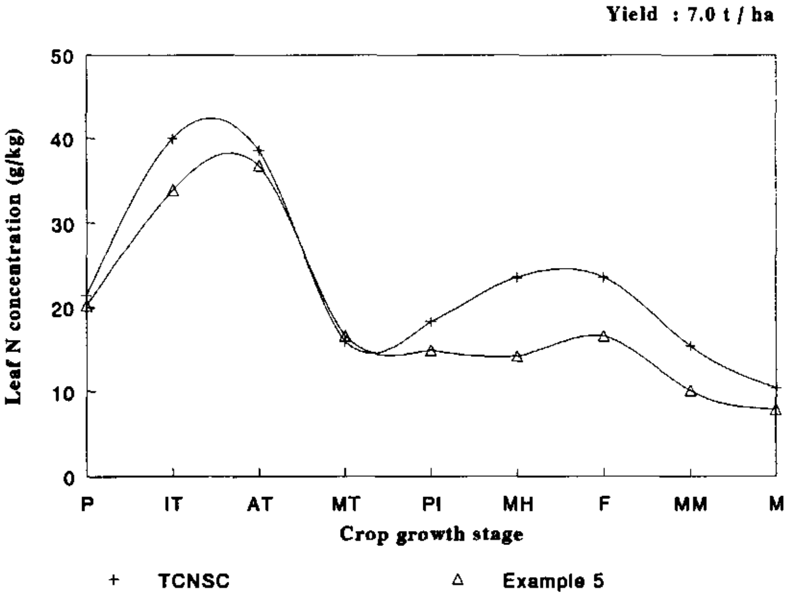

Figure 2e. Example 5 of $n_L(t)$ associated with a grain yield lower than 8 Mg ha^{-1}. Treatment details are given in Table 4.

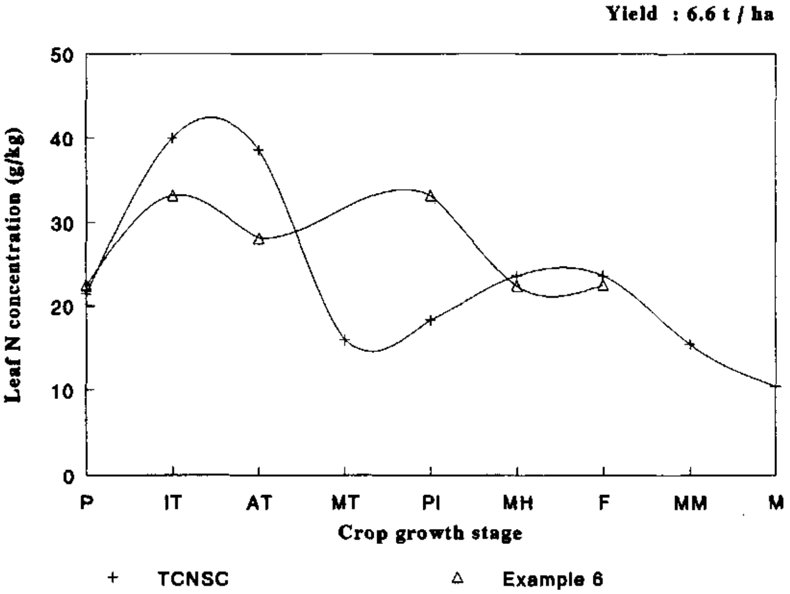

Figure 2f. Example 6 of $n_L(t)$ associated with a grain yield lower than 8 Mg ha^{-1}. Treatment details are given in Table 4.

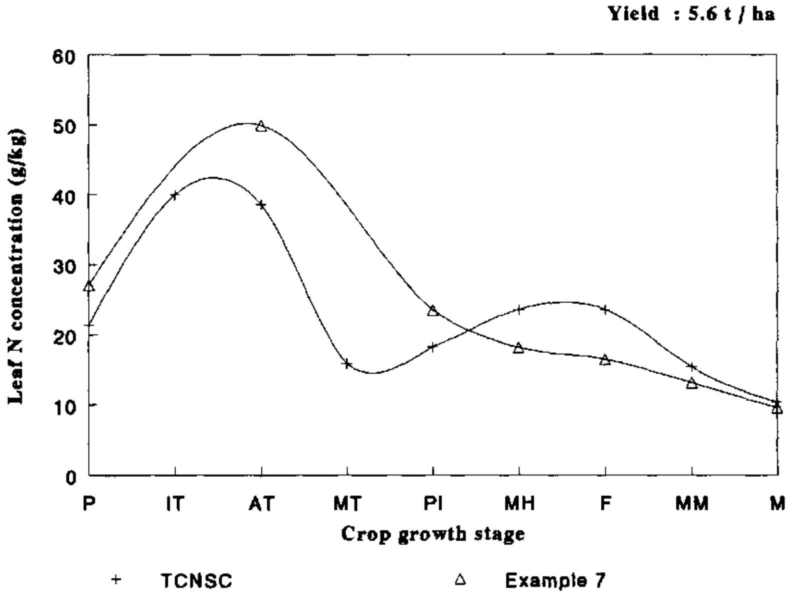

Figure 2g. Example 7 of $n_L(t)$ associated with a grain yield lower than 8 Mg ha^{-1}. Treatment details are given in Table 4.

High N application at flowering does not increase grain yield (Thiyagarajan et al., 1994), but may result in increased grain N concentration (Wopereis et al., 1994).

The nearly 10 Mg ha^{-1} yield situations encountered at IRRI are characterized by higher n_L from tillering to flowering (Figure 3). After flowering, n_L was not much different from the reference curve. High n_L from tillering to flowering was associated with more leaf biomass production. The leaf biomass at flowering was 23 % higher for the 10 Mg ha^{-1} case than for 8 Mg ha^{-1}. We conclude that, to obtain yields higher than 8 Mg ha-1, the n_L should be increased above TCSLNC mainly before flowering. This will generally increase both the total leaf biomass (source size), and the panicle and spikelet numbers (sink size).

Example 7 from IRRI (Figure 3a) with no N application (5.6 Mg ha^{-1} grain yield) indicates that the soils at IRRI are capable of supplying enough N at the initial stages, but that complete omission of N application leads to yields below 8 Mg because n_L drops below TCSLNC after the PI stage. N application at PI can lift the the yield to 8 Mg ha^{-1} and more (Wopereis et al., 1993).

Raising n_L above the TCSLNC level may not always result in yields of 8 Mg ha^{-1} or more. Excessive growth of leaf biomass was observed in Experiment 1, with N application of 400 kg ha^{-1}. Possibly, a high proportion of assimilated N was sequestered into storage pools as amides (Marschner, 1986). Also, even slight excesses of N may lower the percentage of ripened grains (Matsushima, 1976).

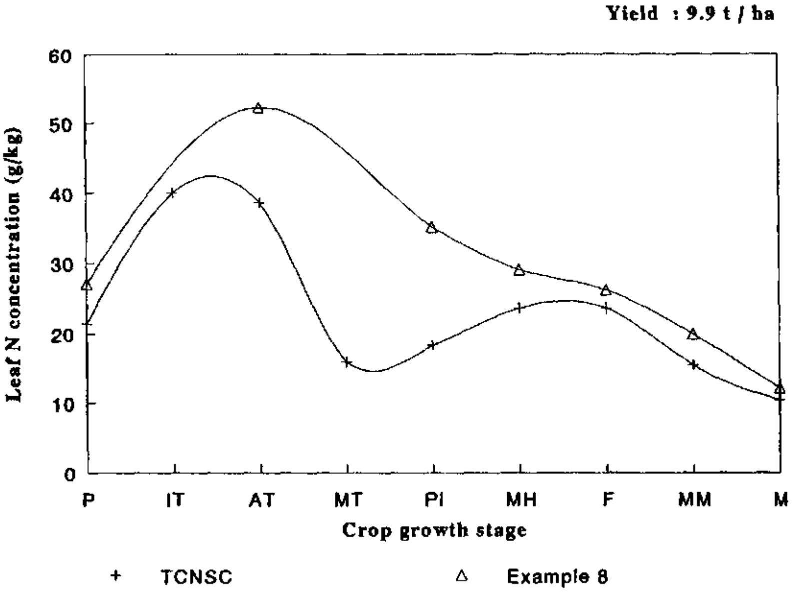

Figure 3a. Time course $n_L(t)$ in Example 8, associated with a grain yield exceeding 8 Mg ha^{-1}. Treatment details are given in Table 4.

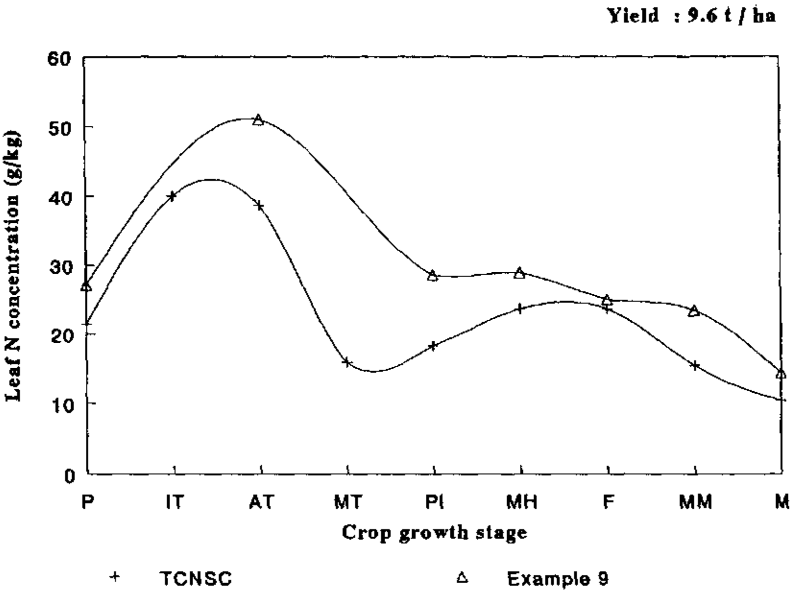

Figure 3b. Time course $n_L(t)$ in Example 9, associated with a grain yield exceeding 8 Mg ha^{-1}. Treatment details are given in Table 4.

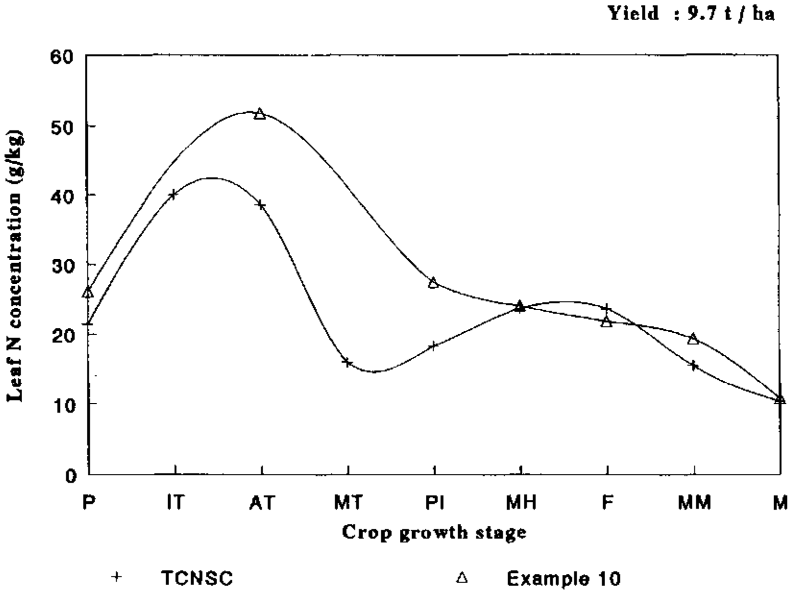

Figure 3c. Time course $n_L(t)$ in Example 10, associated with a grain yield exceeding 8 Mg ha^{-1}. Treatment details are given in Table 4.

Implications of TCSLNC for fertilizer management

The TCSLNC curve can be divided into four parts based on the shape of the curve (Figure 4). The first ascending part (Part I) represents the period of crop establishment after transplanting, and the initiation of the first tillers. Growth is slow, and N accumulates during this phase. Yoshida (1981) pointed out that the tillering rate increases linearly with N content up to $n_L=0.05$. Whether N is applied or not, there is accumulation of N in the leaves during this period. If the soil can supply the required N to raise n_L to the desired level, external N supply can be avoided until AT or later. The results obtained in Experiments 1-5 (Table 1) indicate that the soils of the sites under study can supply sufficient N to meet the TCSLNC level up to AT. The native soil supply would not be sufficient, however, for a 10 Mg ha^{-1} yield goal (Example 2, Figure 2b). Even 150 kg N applied at 10 DAT (Example 1, Figure 2a) could not elevate the n_L curve to values recorded at IRRI. Improving the soil fertility to still higher levels through continuous organic manuring will be imperative to achieve 10 Mg yields in the experimental sites of Aduthurai and Thanjavur. Other, yet unknown, soil conditions may play a major role, too, in enabling high N uptake rates during early crop growth.

Table 4. Treatment details of the examples shown in Figure 2.

Example No.	Location	Year	Variety	N application details
1	Thanjavur	1991-92	CR 1009	150 kg N ha^{-1} applied at 10 DAT
2	Thanjavur	1991-92	CR 1009	No N applied
3	Thanajavur	1992	IR 64	125 kg N ha^{-1} as Sesbania rostrata incorporated 15 days before planting
4	Thanjavur	1992	IR 64	125 kg N ha^{-1} applied in 10 equal splits at 0(P),7,14,21(AT),29,35(MT),42(PI),49,56 and 63(F) DAT
5	Aduthurai	1991-92	CR 1009	150 kg N at 10 DAT 100 kg N ha^{-1} at PI
6	Aduthurai	1992	IR 64	200 kg N ha^{-1} applied in 5 equal splits at 16,24(AT), 32(PI),43, and 58(F) DAT
7	Los Baños	1992	IR 72	No N applied
8	Los Baños	1992	IR 72	180 kg N in 2 splits before PI
9	Los Baños	1992	IR 72	180 kg N in 2 splits before PI and 45 kg N ha^{-1} at F
10	Los Baños	1992	New line	180 kg N in 2 splits before PI and 45 kg N ha^{-1} a F

Development stages are indicated as P (transplanting), AT (Active Tillering), MT (Mid-Tillering), PI (Panicle initiation), and F (Flowering).

The first descending part of the curve (Part II) in TCSLNC represents the active vegetative growth of the crop and signifies the dilution of n_L due to rapid dry matter accumulation. Increasing n_L at this stage results in more leaf biomass. In short duration varieties, MT and PI coincide and the curve will be slightly different. Matsushima (1976) advocated a decrease in the N supply during the growth stage corresponding to 42-18 days before heading (coinciding with the period between MT and PI), to prevent lodging by reducing culm and leaf stretching. This leads to plants with short panicles and erect, thick leaf blades.

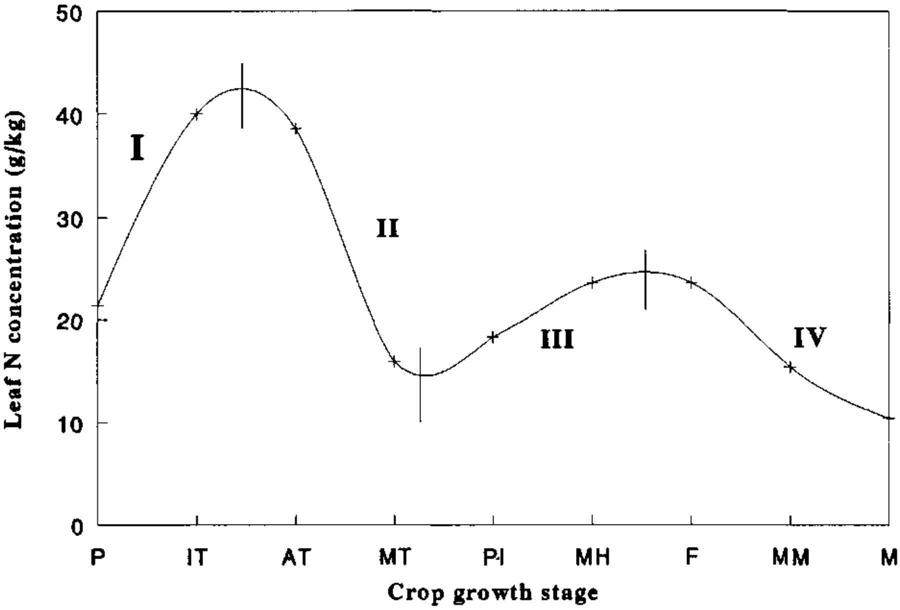

Figure 4. The four segments of the Time Course of Sufficient Leaf Nitrogen Concentration curve.

The rise of n_L after PI (Part III) indicates, in our opinion, that n_L has to be increased from PI onward in order to reach the desired level by the time of flowering, as this is no longer possible at later stages. Concomitantly, there will be increase in leaf biomass up to flowering. This ensures the existence of sufficient green leaf mass for photosynthesis after flowering, upto harvest. A slight increase in nL is often observed even when no additional N is applied, and this could be due to a temporarily enhanced root activity (Heenan & Bacon, 1987). N application at PI must be adequate to boost the n_L to the desired level by MH, and support its rising up to the F stage. Where the native soil N supply enables the maintenance of the desired n_L up to PI, (e.g. at the IRRI site), N application can be delayed up to PI; yield variations are then fully controlled by variations in the crop's N status between PI and F (Wopereis et al., 1993).

The decline of n_L after F (Part IV) indicates the ageing of leaves and the translocation of N to the grains. Possibly, the crop may also loose some of its N (Sivasamy et al., 1994). Maintenance of n_L to the desired level ensures the presence of sufficient green leaves which is essential for adequate carbon assimilation for grain filling.

The n_L observed in treatments yielding near 10 Mg ha^{-1} were only slightly higher than TCSLNC during the postflowering phase (Figures 3). The curves differed more markedly during the AT to F stages, where nL was much above TCSLNC. To achieve yields of more than 8 Mg ha^{-1}, it seems imperative to boost n_L above the TCSLNC level from the AT to the F stage. Example 10 (Figure 3c) suggests that for 10 Mg ha^{-1} yield nL need not exceed the TCSLNC level. Yoshida (1981) reported that the required leaf N can be met when N absorption by the crop is continued after heading, or when a high N content of the vegetative parts is attained before heading, so that the total amount of N absorbed by the time of heading is sufficient to support translocation during ripening. Matsushima (1976) reported yields of 5.6 to 10.2 Mg ha-1 with n_L between 40 and 50 g kg-1 at IT, which subsequently decreased continuously to 10-20 g kg-1 at maturity. Wopereis et al. (1993) concluded that N absorbed after F by a crop deprived of N prior to flowering was helpful only to increase grain N content, not to increase grain yield. The n_L required from F to H for 10 Mg ha^{-1} may well be the same as that dictated by the TCSLNC curve. This has to be verified.

Conclusions

The nitrogen concentration n_L in the green leaves of rice plants was highest during the tillering stage and declined thereafter. Variations observed in n_L due to variations in native soil supply and fertlizer application were limited; n_L could not be increased dramatically, as additional N uptake leads to additional leaf production. In order to achieve a target yield of 8 Mg ha-1, it is required that leaf N concentration be maintained above a defined level, the Time Course of Sufficient Leaf Nitrogen Concentration (TCSLNC) throughout the entire crop growth period. If n_L drops below the TCSLNC curve during any stage of crop development, the grain yield will be less than the target of 8 Mg ha^{-1}. For yield goals of 10 Mg ha^{-1}, n_L should be above the TCSLNC curve from tillering to flowering. The strategy of N application in transplanted rice can be based upon the TCSLNC curve, given the length of the period during which soil conditions allow sustainance of n_L above a level corresponding to a given target yield. The course of $n_L(t)$ required for a 8 Mg ha^{-1} grain yield level was defined in this study.

Acknowledgements

The inspiration to the TCSLNC concept stemmed from the observations of Matsushima (1976), who stated that "the world of rice plants is composed of regularity, order and rules, though many of them are still too complicated for us to comprehend". The senior author wishes to express his admiration to the renowned rice scientist.

The encouragements by Dr.Abdul Kareem, Director, Tamil Nadu Rice Research Institute, Aduthurai are also gratefully acknowledged.

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Comparing different methods for soil solution sampling in puddled rice fields

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Abstract

This study compares destructive soil sampling/centrifugation and *in situ* sampling of soil solution using microporous polymer tubes (Rhizon Soil Solution Samplers; RSSS) as methods to sample soil solution, and investigates the relationship between solution and exchangeable ammonium (NH_4^+). Both sampling methods gave similar results in unfertilized treatments, whereas significant differences were measured in treatments with nitrogen (N) application. There was evidence of preferential withdrawal of soil solution from zones of lowest bulk density using the RSSS method. Soil-core sampling is a better method to obtain quantitative N data integrated over a particular depth range. We observed a highly significant linear relationship between the logs of soil exchangeable and solution NH_4^+ only until PI.

Introduction

Measuring N in flooded ricefields requires reliable methods for both sampling and analysis. Ammonium (NH_4^+) is the predominant form of mineral N in flooded fields and the amounts of NH_4^+ in soil solution or in exchangeable form are commonly used to study N dynamics in soil. In this paper we compare two techniques for sampling of soil solution in wetland soils: destructive soil sampling and *in situ* sampling of soil solution using suction via microporous tubing.

In destructive sampling soil cores are taken from the soil profile. Samples are extracted with salt solutions (KCl, K_2SO_4) for determination of exchangeable NH_4^+ plus solution NH_4^+. Separate subsamples may be used to obtain soil solution via centrifugation in which the concentration of NH_4^+ is measured (i.e. solution NH_4^+). Destructive sampling is laborious, does not allow repeated measurements at the same location and may introduce several errors. The soil solution is usually not completely extracted from the soil and the extracted solution may not be representative (Campbell et al., 1989{xe "Campbell et al.,1989"}). ammonium adsorbed on the soil exchange complex or bound in other solid soil fractions may be released into the solution obtained through centrifugation. (Walworth, 1992). Reports on the influence of centrifugation on the composition of the solution obtained are conflicting (Gillman, 1976; Edmeades et al., 1985; Campbell et al., 1989; Ross & Bartlett, 1990{xe "Ross & Bartlett, 1990"}; Zabowski & Ugolini, 1990; Walworth, 1992{xe "Walworth, 1992"}).

Methods for *in situ* sampling of soil solution using suction have been reviewed by Litaor (1988) & Grossmann & Udluft (1991). The influence of sampling by suction on flow patterns around the sampler and the effect of vacuum extraction on chemical reactions between dissolved constituents and soil solid phases are uncertain (Sposito, 1989{xe "Sposito, 1989"}). Adsorption of ions on the surface of the sampler, outgassing of NH_3 and CO_2, filtration of colloids and macro-molecules, precipitation of solid phases and microbial activities inside the sampler may all change the chemical composition of the extracted solution (Grossmann & Udluft, 1991{xe "Grossmann & Udluft, 1991"}; Hendershot & Courchesne, 1991{xe "Hendershot & Courchesne, 1991"}; Suarez, 1987{xe "Suarez, 1987"}).

The objectives of this study were:

a) to compare destructive and *in situ* methods for sampling soil solution of flooded soils;

b) to investigate the relationship between solution NH_4^+ and exchangeable NH_4^+.

Materials and methods

The sampling techniques were evaluated in two field experiments using rice variety IR72 conducted at the IRRI research farm. Characteristics of the soils and the N treatments used are given in Tables 1 and 2.

Table 1. Soil properties of the experimental fields used in Experiments 1 and 2.

Soil properties	Experiment 1	Experiment 2
Texture	silty clay	silty clay
CEC (cmol kg^{-1})	33.6	29.4
Soil organic C (g kg^{-1})	20.8	15.0
Soil organic N (g kg^{-1})	2.4	1.4
pH (H_2O)	5.8	6.3
Olsen P (mg kg^{-1})	9.0	13.5

Experiment 1

This study was conducted in the dry season of 1992 (January - May) as part of a field experiment designed to investigate N supply as a yield determinant. Three N treatments with urea as the N source were replicated 4 times in a randomized complete block design (Table 2). Basal applications of N were broadcast and incorporated 1 day before transplanting. Immediately prior to N topdressings, floodwater depth was reduced to a point where the soil was saturated without standing water. Sampling was done at 1 day after TP (1 DAT), 19 DAT, 28 DAT, panicle initiation (PI, 42-43 DAT), PI+4d, PI+10d, first flowering (FF, 68-69 DAT), FF+14d and physiological maturity (PM, 96-99 DAT). At 1 DAT, only extractable NH_4^+ was determined. Soil samples were taken from 0-5, 5-10 and 10-15 cm depth with the truncated barrel of a 250 ml syringe 2.5 cm in diameter. For each plot, three randomly located cores from a 2.4 m^2 area were combined for each depth interval and stored over ice in plastic bags which were closed after excluding air. In the laboratory, the plastic bags containing the bulked soil samples were kneaded for homogenization. Soil extractable NH_4^+ was determined by shaking 20 g wet soil in 60 ml 0.5M K_2SO_4 for 30 min. The extracts were filtered through Whatmans no. 42 filter paper and stored frozen prior to analysis. Soil solution samples were obtained by centrifuging another subsample of 20 g wet soil at 10,000 r.p.m. for 5 min. Three ml of solution was removed using a pipette and acidified with 0.1 ml 6N HCl. An initial experiment showed no effect of acidification of the soil solution on the NH_4^+ concentration{xe "Gaunt, 1993"}. Ammonium-N in both extracts was determined using a modified Indophenol blue method (Kempers & Zweers, 1986{xe "Kempers & Zweers, 1986"}; modified by Gaunt, 1993{xe "Gaunt, 1993"}) and exchangeable NH_4^+ was calculated after subtracting solution NH_4^+ present in the extracted sample. In addition, soil solution samples were taken at 19 and 28 DAT using microporous polymer tubes (Rhizon Soil Solution Samplers, RSSS) distributed by Eijkelkamp Agrisearch Equipment, The Netherlands.The RSSS had a diameter of 2.3 mm (inner diameter 1 mm), a pore size of 0.1 µm and a

Table 2. Rates and timing of nitrogen applications in the field experiments.

	Basal:			Topdressed					
	N-Rate (kg ha^{-1})	Transplanting		Mid tillering		Panicle initiation		Flowering	
		N[1]	DAT[2]	N	DAT	N	DAT	N	DAT
Experiment 1	0	0		0		0		0	
	180	120	-1	60		60	42	0	
	225	60	-1	60	24	60	42	45	68
Experiment 2	0	0		0		0		0	
	200	80	-3	40	25	40	43	40	63

[1] N N applied (kg ha^{-1})

[2] DAT Days after transplanting at which applied

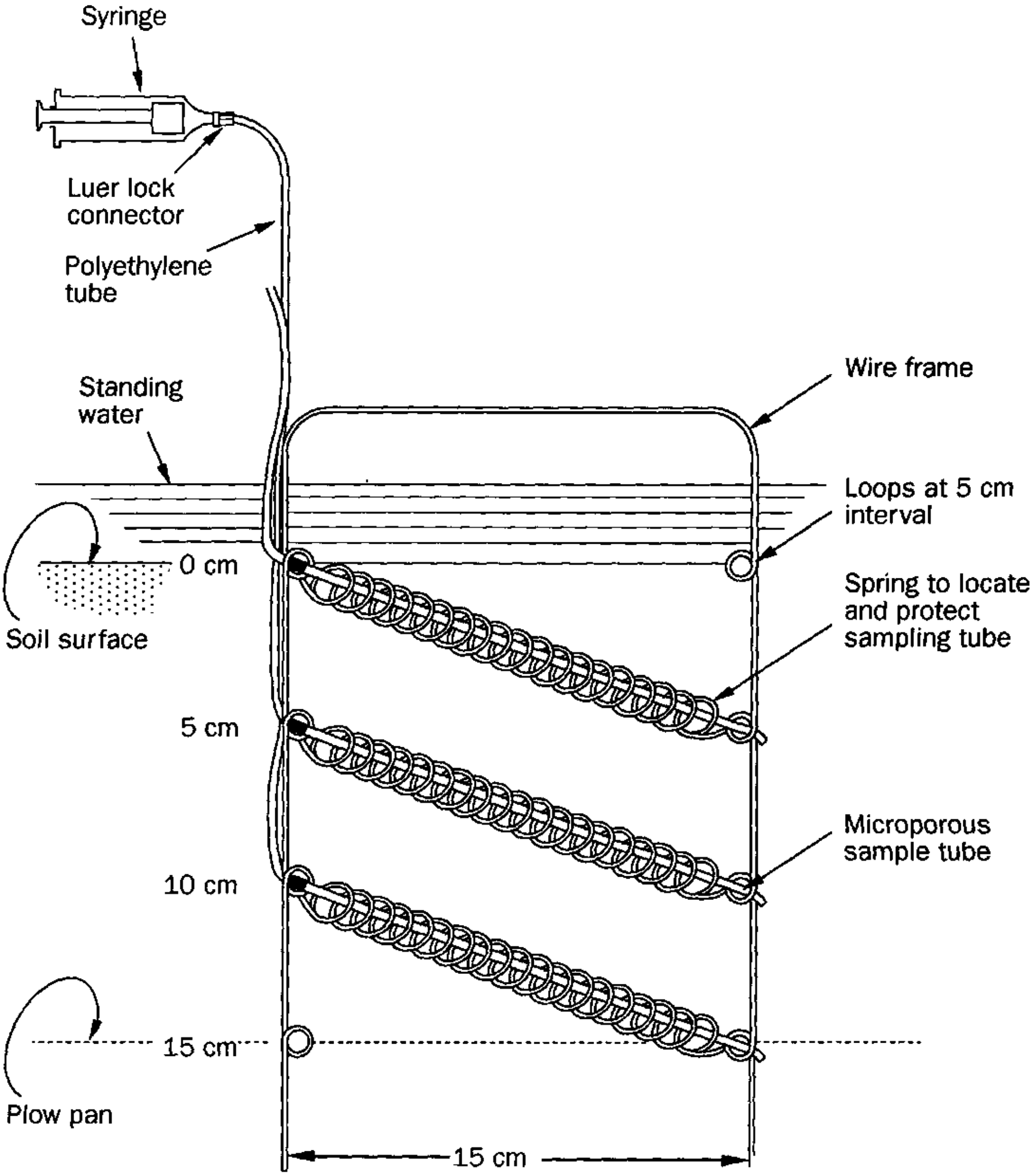

Figure 1.Installation of solution sampling tubes (RSSS) in Experiment 1.

dead volume of 0.5 ml. They do not have ion exchange capacity. In each field plot, five wire frames containing 3 RSSS were installed to obtain an average sample over a particular depth range (Figure 1). Soil solution samples (each approx. 10 ml) were taken from the RSSS and combined into one composite sample per depth range. Prior to sampling, the tubes were drained by withdrawing and discarding a small volume of solution (± 2 ml). Samples were taken using syringes and stored under iced water in the field. Combined samples from the 5 replicates were acidified with 0.1 ml 6N HCl and analyzed for NH_4^+ using the modified Indophenol blue method.

Experiment 2

In the 1993 dry season two adjacent fields, each 2,000 m^2 in size (25 by 80 m), were sampled. Field 1 was unfertilized and field 2 received 200 kg N ha^{-1} as urea (80 kg N basal + 120 kg N topdressed into the floodwater in 3 splits (Table 2). Eight sampling locations arranged on a 2 by 4 square grid with 20-m intervals were used in each field to obtain soil cores and soil solution samples. At each sampling point, soil samples were taken from a 2 by 2 m sampling plot using a PVC pipe with a diameter of 5 cm. Three depth intervals (0-5, 5-10 and 10-20 cm) were sampled and 3 samples for each depth were bulked into one sample. Two subsamples of 20 g wet soil were taken for determination of exchangeable NH_4^+ and solution NH_4^+ using the methodology described above. The soil was centrifuged at 10,000 r.p.m. for 15 min. to obtain soil solution. At the center of each field sampling location, four RSSS were installed diagonally over the depth range 2-10 cm. Soil solution samples were collected using 10-ml vacutainers (evacuated vials) that where directly connected to the sampler via a needle and luer-lock connectors and acidified. Samples were combined into one composite sample per depth and analyzed for NH_4^+ using the modified Indophenol blue method. All sampling was done at weekly intervals until panicle initiation. Later, samples were taken bi-weekly.

Results and discussion

Suction versus centrifugation

Ammonium concentrations in solution samples taken by the two sampling methods, in experiment 1, were significantly different for treatments that received N, but not in the 0-N treatment (Table 3). The microporous tubes were installed diagonally so as to obtain an average soil solution over a sampling depth. There appears to have been preferential withdrawal of solution from the zones of lower bulk density nearer the soil surface. The NH_4^+ concentrations in 0-5 cm tended to be lower with the RSSS method, indicating that floodwater with a low NH_4^+ content was drawn into the sample. In addition, at 28 DAT the treatment that received a topdressed N application 4 days before sampling showed significantly higher NH_4^+ concentrations in the upper 5 cm with the RSSS method suggesting preferential flow. The relationship between exchangeable NH_4^+ and solution

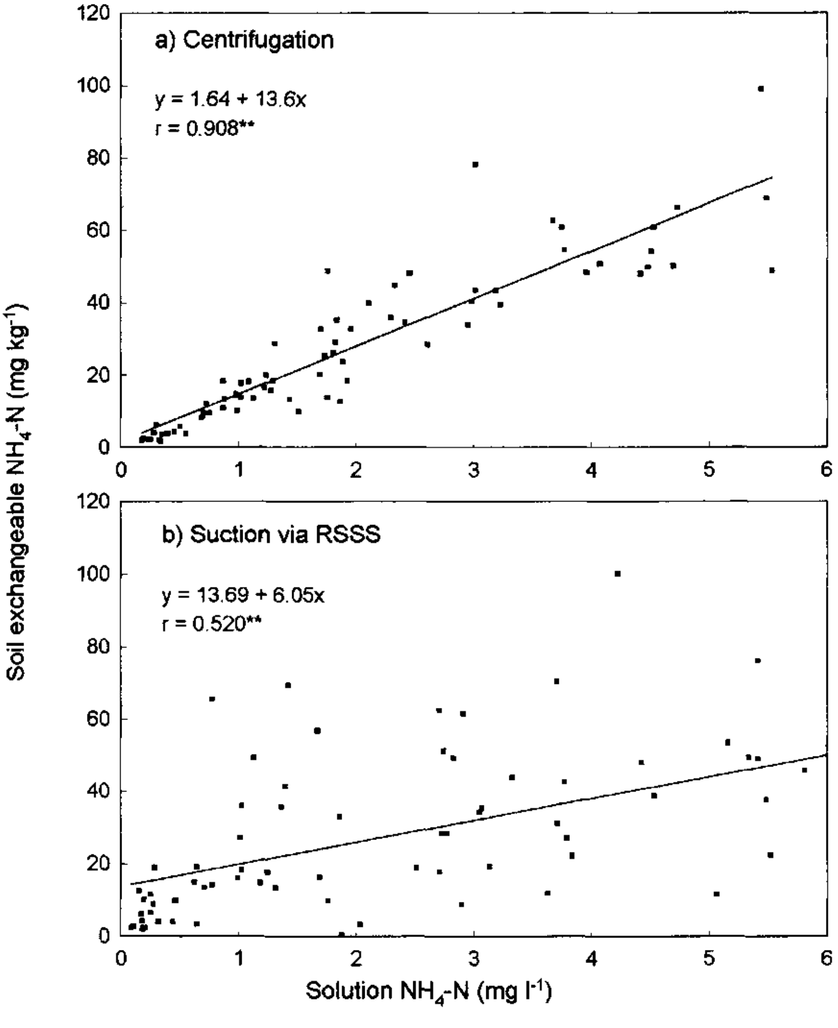

Figure 2. Plots of soil exchangeable vs. solution NH4+ for samples taken by centrifugation and suction (RSSS) in Experiment 1 (19 and 28 DAT).

Table 3. Comparison of NH4+ concentrations in soil solution obtained at 19 and 28 days after transplanting (DAT) by centrifugation and suction through microporous tubing (RSSS) in Experiment 1.

Basal N	Topdressed N at 24 DAT	Depth (cm)	Solution ammonium (mg N kg^{-1})			
			19 days after transplanting		28 days after transplanting	
			Centrifugation	RSSS	Centrifugation	RSSS
0	0	0-5	0.78a*	0.23b	0.28a	0.14a
		5-10	1.05a	0.74a	0.29a	0.20a
		10-15	1.06a	1.04a	0.51a	0.46a
60	60	0-5	2.44a	1.34b	3.14b	5.14a
		5-10	2.04b	3.28a	1.16a	2.29a
		10-15	1.48b	3.31a	1.50a	2.49a
120	0	0-5	4.61a	2.81b	2.35a	0.84b
		5-10	3.88b	5.76a	3.86a	2.14b
		10-15	1.83b	5.47a	3.60a	3.89a

*a and b compare means between sampling method for each treatment and depth. Means followed by the same letter were not significantly different as determined by LSD test ($P < 0.05$).

NH$_4^+$ also differed between the two methods of solution sampling (Figure 2).Exchangeable and solution NH$_4^+$ were better correlated when solution samples were obtained by centrifugation ($r=0.908$) than by suction using RSSS ($r=0.520$).

Makarim et al. (1991) used the same type of RSSS installed horizontally to study N dynamics in an irrigated puddled rice field in Indonesia. their experiment. Treatment and depth effects could be clearly distinguished in their experiment. They described the relationship between solution NH$_4^+$ measured with RSSS and exchangeable NH$_4^+$ with a Freundlich isotherm ($r^2=0.64$).

Solution versus exchangeable NH$_4^+$

In both experiments, a highly significant linear relationship existed between the logarithms of solution NH$_4^+$ and exchangeable NH$_4^+$ (i.e. a Freundlich relationship) until panicle initiation (PI). Only weak correlations occurred after PI (Figure 3). The relationship between solution and exchangeable NH$_4^+$ apparently breaks down when there are low absolute NH$_4^+$ values in the soil. Makarim et al. (1991) attributed a similar observation to competition with other cations for exchange sites at low N levels in the soil. Our data support this hypothesis. Another explanation would be rhizosphere acidification which tends to increase soil:solution NH$_4^+$. As the root system develops this ratio would increase and vice-versa as the root system declines after PI (Kirk & Solivas, 1994).

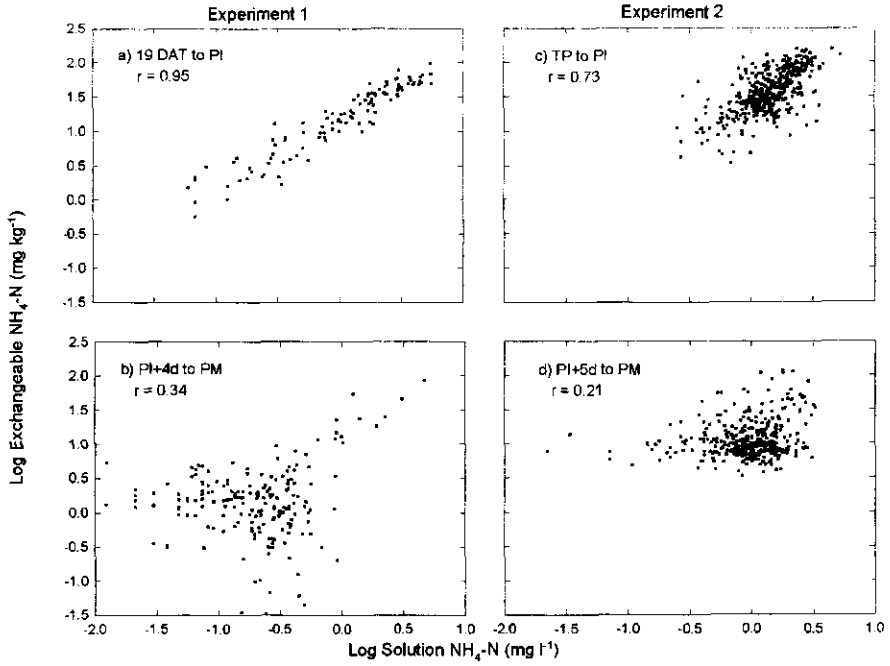

Figure 3. Relationship between soil exchangeable and solution NH_4^+ (by centrifugation) from transplanting (TP) to panicle initiation (PI) and from PI to physiological maturity (PM) in both field experiments. DAT = days after transplanting.

Conclusions

Centrifugation to obtain soil solution was a better method for integrative soil solution sampling over a depth range in flooded rice fields than solution sampling through suction using microporous tubes. Poor performance of the suction method for this particular purpose may have been due to the method of installation. Horizontal installation of tubing may reduce preferential flow effects. Microsamplers of the RSSS type could be appropriate for studies on micro-variation, dynamics of solutes, and root activities in relationship to soil solution chemistry. This method should be also a good choice if data for stochastic or mechanistic process modeling at the micro-scale are needed. The low dead volume, chemical neutrality and ease of use in the field for repeated sampling are major advantages.

Bulking of soil samples and extraction of solution via centrifugation reduces the inherent soil and solution micro-variation and apparently gives more reliable estimates of the areal mean concentration integrated over a particular soil depth. This method should be preferred for mass balance studies and for studies where average sampling is needed. However, there is a need to study the effects of homogenization on the within bulked-sample variability and to determine the optimum volume or weight of a subsample taken for exchangeable NH_4^+ determination.

Solution NH_4^+ is highly variable in the field and the relationships between exchangeable and solution NH_4^+ are changing over time. After PI of rice, exchange isotherms obtained from data at earlier growth stages no longer hold. For many purposes observations of extractable NH_4^+ alone are inadequate, even if an isotherm is available. Influences of other cations on the NH_4^+ exchange equilibrium in flooded soils need further research and should be taken into account within nitrogen process models.

Acknowledgements

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A mechanistic model of N dynamics in flooded soil

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This paper reports further developments of the model of Rachhpal-Singh & Kirk (1993a,b).

A. Effect of nitrification-denitrification and further sensitivity analyses

For simplicity, N losses by nitrification-denitrification were not allowed for in the original model. They are now included as follows.

(i) It is assumed that there is a particular concentration of O_2 in the soil solution below which nitrification does not occur and above which it occurs at a rate independent of the O_2 concentration.

(ii) The width of the zone at the soil-floodwater interface in which the O_2 concentration is above the critical value is a given and has the value z_{ox}. In fact, z_{ox} depends on the O_2 concentration in the floodwater, the rate of O_2 movement from the floodwater into the soil, and the rate of O_2 consumption in the soil in inorganic reactions and in microbial processes, including nitrification. But for simplicity we do not deal with these processes explicitly in the model.

(iii) The rate of nitrification, R_{nit}, varies with the concentration of ammoniacal-N in the soil solution, $[NH_4]_L$, according to a Michaelis-Menten type relation:

$$R_{nit} = \frac{V_{max}[NH_4]_L}{K_M + [NH_4]_L} \quad (1)$$

where K_M and V_{max} are constants. Recognizing that the nitrification rate will also be influenced by changes over z_{ox} in soil bulk density, pH, temperature and other factors, and that the effects of changes in these factors will to some extent cancel each other out, we assume V_{max} is constant over z_{ox} and define it on a per unit soil volume basis.

(iv) All the N nitrified is assumed to diffuse into the reduced soil and be lost through denitrification. In fact some of the NO_3^- may be assimilated by roots or microbes before reaching the reduced zone, and so our calculation represents an upper estimate. Available C is not likely to limit the rate of denitrification of NO_3^- in the reduced zone (Reddy et al., 1982; Buresh & De Datta, 1990).

(v) Two mol of H^+ are produced for each mol of NH_4^+ nitrified, and 1 mol of H^+ is consumed per mol of NO_3^- denitrified. We assume that the net change (1 mol of H^+ produced per mol of NH_4^+ nitrified) takes palce at the site of nitrification.

The nitrification rate term, given by Equation (1), is included as a sink term on the RHS of the NH_4-N movement and reaction continuity equation (Rachhpal-Singh & Kirk, 1993a, Eqn (20)).

We selected appropriate ranges of values for z_{ox}, K_M and V_{max} from a literature search and personal observations. Personal observations and the results of theoretical modelling (Kirk et al., 1990) indicate that an appropriate range for z_{ox} is 4-16 mm. Net denitrification losses from continuously flooded soils estimated from ^{15}N-balance studies range from 3 to 60% of fertilizer N applied at rates of the order of 100 kg ha^{-1} (Buresh & De Datta, 1990; De Datta et al., 1991; Freney et al., 1990; Reddy & Patrick, 1986). By assuming a z_{ox} value of 10 mm, the nitrification rates required to produce these losses are in the range 10-130 μ mol dm^{-3} h^{-1}. Reported directly measured nitrification rates in the floodwater-soil interface are in the range 0-60 μmol dm^{-3} h^{-1} (Katyal et al., 1988; Patrick & Reddy, 1977; Watanabe et al., 1981). Maximum nitrification rates in unsaturated aerobic soils exceed 100 μmol dm^{-3} h^{-1} (Darrah et al., 1985). We take from Knowles et al. (1965) $K_M = 100$ μM.

The revised model predicts strong interactions between the variables controlling nitrification rates and the parameters for atmospheric/floodwater turbulence and the distribution of NH_4 with depth (urea hydrolysis rate, percolation rates, NH_4-N buffer power). Some results are:

* As z_{ox} and/or V_{max} is/are increased, the total N loss tends to increase -- though the increase may be negligible at high turbulence -- but less N is lost through NH_3 volatilization because the flux of NH_4-N into the floodwater is decreased.

* As k_U (the urea hydrolysis rate constant) increases, the increase in nitrification with increase in z_{ox} or V_{max} is amplified, and so net losses increase greatly. In consequence, at high k_U values, net losses at low atmospheric/floodwater turbulence may approach those at high turbulence.

* If z_{ox} or V_{max} are such that nitrification rates are high, the differences in net losses between high and low turbulence are small.

* At high water percolation rates (i.e., high K_{sat} in the impermeable layer), NH_3 losses may be greatly reduced but if nitrification rates are moderate, net losses may be only slightly decreased.

* k_U has a smaller effect on the rate of nitrification than on NH_3 volatilization, and so the increase in net loss as a result of increases in k_U is similar to the increase in NH_3 volatilization.

* At high water percolation rates, the effect of k_U is smaller.

* The effect of the H^+ generated in nitrification-denitrification on NH_3 volatilization losses is small.

- If the nitrification rate is sufficient, the main control on net losses is the distribution of NH_4-N with depth -- i.e., k_U, NH_4-N buffer power, K_{sat}, floodwater depth are the important variables; the effects of turbulence and variables controlling floodwater chemistry are small.

  The original sensitivity analyses used as "standard" fairly high values of the parameters for floodwater and atmospheric turbulence. Some results with the revised model are:

- At high turbulence ($z_L = z_G = 25$ μm), changes in the initial soil pH in the range 6.5-7.5, alkalinity (i.e., $[Cat^+]_L - [An^-]_L$) in the range 0.5-4.5 mM, and soil CO_2 production (R_{orgC}) in the range 5-40 μmol dm^{-3} (soil) h^{-1} had little effect on cumulative NH_3 loss over 10 d with other parameter values as in Rachhpal-Singh & Kirk (1993b) Table 1. Decreases in the NH_4-N buffer power as a result of decreases from 0.225-0.08 dm^3 kg^{-1} in the Freundlich coefficient for NH_4^+ sorption "*a*", did substantially increase cumulative NH_3 loss.
- At low turbulence ($z_L = z_G = 1000$ μm), the above changes all had much greater effects and there were interactions between them. Thus, decreases in alkalinity substantially decreased cumulative NH_3 loss, particularly at low initial soil pH and low soil CO_2 production.

B. Simplification of the model

Since the original model requires a large amount of computing time (c. 30 min of CPU time on a VAX 4000 to simulate 10 days of real time), it is not practical for exhaustive sensitivity analyses and for linking to a crop growth model to explore the relation between soil N dynamics and plant uptake. The initial sensitivity analyses showed that in many circumstances, long-term (i.e., greater than the immediate few days following fertilization) cumulative N losses were not very sensitive to the parameters controlling floodwater chemistry: any NH_4-N in the soil solution in the vicinity of the floodwater is lost as gas very rapidly and the rate-controlling step in gas loss is the movement of NH_4-N towards the floodwater. An implication is that a greatly simplified model, ignoring the niceties of floodwater chemistry, would be adequate for many purposes. The sensitivity of the revisedoriginal model indicates the conditions in which such a simplified model would be adequate.

In the simplified model, NH_3 loss from the floodwater is treated as a simple first order process:

$$F_{GA} = -k\,[NH_4]_{L0} \qquad (2)$$

where F_{GA} = NH_3 flux across the water-atmosphere boundary,
$[NH_4]_{L0}$ = NH_4-N concentration in solution at the floodwater-soil interface,
and k = rate constant summarizing the effects of all variables influencing the relation F_{GA} and $[NH_4]_{L0}$.

Table 1. Experimentally measured k_{mean} values (dm h^{-1})

Site	av. k_{max}	av. k_{min}	k_{mean}	Reference
Los Baños	0.038	0.007	0.017	Fillery et al. (1984)
Muñoz	0.068	0.007	0.026	Fillery et al. (1984)
Mabitac	0.060	0.007	0.024	De Datta et al. (1989)
Griffith	0.054	0.006	0.021	Simpson et al. (1984)
Griffith	0.056	0.005	0.021	Freney et al. (1988)
Xinxiang	0.059	0.010	0.026	Zhu et al. (1989)

With this simplification, it is not necessary to consider the movement and reaction of carbonate species and acidity between the floodwater and soil. The movement and reaction of urea and NH_4-N between the floodwater and soil and their mass-balances in the floodwater are described by the same equations as the original model (Rachhpal-Singh & Kirk, 1993a, Eqns (1) and (2) and Eqns (18)-(22)), and nitrification-denitrification is allowed for as above. The simple model has 12 input parameters whereas the original model has 19, and it takes c. 3 min of CPU time on a VAX 4000 to simulate 10 d of real time, as opposed to c. 30 mim.

Table 1 gives values for the rate constant k derived from NH_3 fluxes and corresponding floodwater ammoniacal-N concentrations reported in the literature for ricefield experiments. The calculated k values vary diurnally in accordance with changes in floodwater pH, temperature, wind speed, etc. The diurnal changes in -- and differences between locations -- may be as much as two orders of magnitude. We calculated weighted-mean k values over the diurnal cycle by assuming a sinusoidal change over 12 daylight hours and a constant value overnight, i.e.,

$$k_{mean} = \frac{k_{max} - k_{min}}{\pi} + k_{min} \qquad (3)$$

where k_{max} and k_{min} are the maximum and minimum values over the day. k_{mean} values calculated with Equation (3) agreed well with the true means calculated from individual measurements over the day. The model predictions were not much altered when a diurnally varying k value was replaced by the corresponding k_{mean} value.

Over a wide range of the model's other input values, cumulative N loss was not sensitive to k_{mean} at values greater than a critical value (k_{crit}) of 0.05 dm h^{-1}. As expected, N loss was sensitive to urease activity, soil NH_4-N buffer power, floodwater depth, and the degree of fertilizer incorporation in the soil, but the effects of these variables were not sensitive to k_{mean} if it exceeded k_{crit}.

A decrease in NH_3 loss caused by a decrease in k_{mean} below k_{crit} does not cause net N loss to decrease by the same extent because the resultant increase in the concentration of NH_4-N in the aerobic zone results in increased nitrification-denitrification. If z_{ox} (the thickness of the oxidized zone in which nitrification occurs) is sufficiently small, then the limit that NH_4-N diffusion from the soil towards the floodwater imposes on nitrification-denitrification will be similar to that it imposes on NH_3 volatilization, and it is then valid to lump-together nitrification-denitrification and NH_3 volatilization in the model.

For the set of standard parameter values used in the original sensitivity analysis (Rachhpal-Singh & Kirk, 1993b), k_{mean} values calculated with the original model were somewhat higher than those in Table 1. The values were brought into the range in Table 1 when the atmospheric- and floodwater-turbulence parameters were given the "low turbulence" values in Rachhpal-Singh & Kirk (1993b) Table 1. At these values, cumulative NH_3 losses are sensitive to the parameters controlling floodwater chemistry.

The simple and original models were equally sensitive to urease activity, floodwater depth and the NH_4-N buffer power over a range of turbulence and equivalent k_{mean} values. The predicted interactions between urease activity and floodwater depth were similar; viz., when urease activity is low or moderate, deep floodwater reduces NH_3 loss substantially, but at high urease activity and high atmospheric-and floodwater turbulence, floodwater depth has no significant effect on N loss. The models had similar sensitivities to the soil NH_4-N buffer power; viz., N losses are greater when the buffer power is low because the rate of diffusion of NH_4-N from the soil into floodwater is greater.

C. Effects of and on plant uptake

It is clear that soil and fertilizer N are used least efficiently when the fertilizer is applied before the plant sink for N is developed. Also, luxurious N uptake and growth during early growth stages can later cause lodging and increased disease susceptibility. We need to be able to predict how far fertilization can be delayed in particular circumstances without compromising final yield potential.

The simple model predicts the vertical distribution of NH_4^+ in the soil and the changes in this distribution with time. We need to link the simple model to ORYZA1 in such a way that we can predict how N uptake affects this distribution -- and hence how uptake affects N losses -- and also how the distribution affects N uptake.

For a given plant N demand, the rate of uptake is potentially limited by (1) root morphology, (2) N uptake capacity per unit root surface, and (3) the rate of N transport through the soil to root surfaces by mass flow and diffusion, which may be altered by root-induced changes in the soil. For plants growing in aerobic soil and taking up N as NO_3^-, root morphology and uptake properties do not limit uptake until soil N levels fall to very low levels (Drew, 1990). But for lowland rice, because the dominant form of plant-available N is NH_4^+, which is far less mobile in soil than NO_3^-, root characteristics and transport through the soil are more important. The simplest model for describing transport-limited nutrient uptake considers that the roots behave as zero sinks for the nutrient. In other words, uptake at the root surface is considered to be so much faster than transport through the soil that it is effectively instantaneous. But such a model results in greatly over-estimated uptake rates for measured lowland rice root length densities and soil solution NH_4-N concentrations (see ten Berge et al. (1993) and below). Therefore a more complicated model is needed.

In the model we are developing, root mass at a given time, as predicted by ORYZA1 from previous growth, is distributed with depth according to a time-dependent exponential function, and the corresponding root length densities at different depths are calculated from a relation for root length per unit root mass. The rate of uptake at a particular depth is then calculated from the root length density and the NH_4-N concentration in solution using a "root absorbing power", α (Nye & Tinker, 1977, Ch. 5). α relates the flux, F, into the root to the concentration in solution at the root surface, $[NH_4]_{La}$:

$$F = \alpha\,[NH_4]_{La} \qquad (4).$$

α is itself a function of $[NH_4]_{La}$ and also of the plant N status. $[NH_4]_{La}$ is calculated with a model in which the concentration profile of NH_4 around the root corresponds to that of a steady-state (Nye & Tinker, Eqn (7.9)):

$$[NH_4]_{La} = \frac{\overline{[NH_4]_L}}{1 + \dfrac{\alpha a}{D_L \theta f} \ln \dfrac{x}{1.65a}} \qquad (5)$$

where $\overline{[NH_4]_L}$ = mean concentration in solution in the depletion zone (given by the concentration at that depth predicted by the simple model),

D_L = NH_4^+ diffusion coefficient in free solution,
θ = soil volumetric water content,
f = diffusion impedance factor,
a = mean root radius,
and x = radius of root exploitation zone (= $1/\sqrt{\pi L_V}$ where L_V = root length density).

Ultimately we need to make α and also the root:shoot dry wt and root dry wt: root length relationships functions of plant N status so that uptake is regulated according to plant N status. There are as yet no reliable data for rice with which to do this, but appropriate experiments are under way at IRRI. For other plants, α generally varies with $[NH_4]_{La}$ according to Michaelis-Menten-type equation: $\alpha = \dfrac{F_{max}}{K_M + [NH_4]_{La}}$. Thus there is some critical $[NH_4]_{La}$ value above which F is independent of $[NH_4]_{La}$. If the critical value is 100 μM, which is a modest value for N uptake by cereals (de Willigen & van Noordwijk, 1987), with $a = 0.1$ mm, Equations (4) and (5) predict that an uptake rate of 5.5 kg ha^{-1} d^{-1}, which is the maximum expected uptake rate in lowland rice (Kropff et al., 1994), is attained independent of rooting density only at $\overline{[NH_4]_L} > 15$ mM. For a soil NH_4-N buffer power of 10, which is a modest value, this would require 150 kg N ha^{-1} averaged over 10 cm of soil.

The above calculations are sensitive to the value of $[NH_4]_{La}$ for maximum intake; reliable values of this are not easily obtained (see Workshop General Discussion; Nye & Tinker, 1977, Ch. 5; de Willigen & van Noordwijk, 1987, Ch. 3). At sufficiently low values, the roots behave as zero sinks but then the model predicts that N demands of the level observed in experiments could be met with smaller root length densities than measured, and it is then necessary to invoke an "effective root length" of the order of a tenth of the true root length to obtain agreement. But given that water uptake is unlikely to dictate root length in lowland rice, and that N uptake therefore does, this seems unreasonable because the plant would be wasting energy in producing excess root mass. In view of the restricted O_2 supply to the root cells involved in N uptake, and also the degradation of the primary root cortex to form aerenchyma and the consequently reduced nutrient-absorbing surface in the cortex, a high value of $[NH_4]_{La}$ for maximum intake seems reasonable.

A further complication may be the effect of root-induced changes in the rhizosphere on the soil NH_4-N buffer power (Kirk & Bouldin, 1991; Kirk & Solivas, 1994). The generation of H^+ in oxidation of Fe^{2+} in the rhizosphere and the release of H^+ from the roots to balance excess intake of cations over anions, together result in impaired access of NH_4^+ to root surfaces, particularly at low concentrations of anions in the soil.

An additional effect of uptake may be to lower the floodwater pH and hence NH_3 loss through the release of H^+ from the roots to balance excess intake of cations over anions. This is allowed for in the original model. From our sensitivity analyses so far, this does not greatly influence cumulative N loss or N recovery. We obtained the largest effects where root densities were high near the floodwater-soil interface (e.g. for a direct-seeded crop as opposed to a transplanted one) because the acidification was taking place nearer to the floodwater. But this effect was much smaller than the effect of the greater N sink nearer the floodwater.

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Nitrogen supply or root function: what governs N uptake in irrigated rice?

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With temperature and solar radiation determined, yield potential of rice is primarily governed by crop nitrogen (N) supply when water, other nutrients, and pests do not limit crop growth. In general, N use efficiency by irrigated rice is considered to be poor, based on the rapid gaseous losses of N that occur in the soil-floodwater system, and low fertilizer-N uptake efficiency (FNUE) based on ^{15}N fertilizer uptake studies. In fact, FNUE by rice is typically comparable to that of other cereals at high yield levels with irrigation when estimates are based on the actual increase in N uptake that results from N application. In several studies, however, the seasonal pattern of N accumulation suggests a period during crop growth when the root system appears to have a reduced capacity for efficient N acquisition. At issue is whether these sluggish uptake periods reflect an actual reduction in root uptake activity, or the lack of an adequate N supply from soil and fertilizer sources.

To address this issue, we developed a N point-placement technique that places the equivalent of 1.2 kg ^{15}N ha^{-1} (99.5% ^{15}N-N enriched) directly beneath a single rice hill at 7 cm depth. The method uses a large gelatin capsule filled with a $(^{15}NH_4)_2SO_4$ solution which is glued to a thin wooden stick 25 cm long and inserted at the appropriate angle to achieve a 7 cm depth beneath the rice hill. Individual capsules are placed below 8 adjacent hills in a 2 x 4 pattern to create a microplot within existing treatment plots of a field experiment. Placement times can occur at specific stages of development such as mid-tillering, panicle initiation (PI), etc. to create several microplots within the same treatment plot. For each placement time, replicate microplots can be established for plant sampling at subsequent growth stages to quantify 15N uptake and partitioning in different plant organs.

This method has the two advantages: (1) the very small dose of added ^{15}N does not influence the N supply imposed on the treated hills or on the surrounding hills in the treatment plot, and (2) it is relatively inexpensive because it utilizes a small quantity of ^{15}N applied only to a few hills in the microplot.

We used the point placement technique in the 1992 DS at the IRRI Research Farm to measure N uptake activity at panicle initiation stage and at flowering in a field experiment with factorial treatments of three N rates (165, 225, and 285 kg N ha^{-1}) and hill spacings to provide 25, 50, and 75 hills m^{-2}. When plants were sampled at 14d after flowering, recovery efficiency from the applied ^{15}N was 65% regardless of whether the ^{15}N was inserted at PI or at flowering. At physiological maturity, further uptake continued from the applied ^{15}N at flowering while there was no further uptake from the PI application. These results demonstrate that root capacity to acquire N did not decrease in the period from PI to early grain filling.

Grain yield in this study ranged from 7.9 to 9.6 t ha^{-1}. Yields were similar in all N-rates, and decreased when hill density was greater than 25 m^{-2} due to increased disease and lodging. Partitioning of ^{15}N within the plant was very sensitive to the time of ^{15}N placement, but insensitive to plant density and N rate. At mid-grainfill, ^{15}N acquired soon after PI was highly enriched in the upper leaves and depleted in the panicles relative to the distribution of total unlabeled N in the plant. The opposite pattern of enrichment was found for ^{15}N acquired after flowering. At physiological maturity, depletion of ^{15}N acquired soon after PI and found in upper leaves at mid-grainfill was considerably less than the ^{15}N depletion in upper leaves from the application at flowering.

These results demonstrate the use of the point-placement technique to monitor root N uptake activity and allocation within the plant. For the SARP Project, we propose this method to test the hypothesis that the rice root system maintains an efficient capacity to acquire N throughout the growing season when an immediately available N supply exists in the root zone and there are no pest problems, other nutrient deficiencies, or water deficits that would reduce root function.

Summary of discussion on modelling N uptake

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In general, N is taken up from aerobic soils as NO_3^-. Because NO_3^- is highly mobile in soils, being, in general, little adsorbed on soil surfaces, its rate of uptake is not very sensitive to root system morphology. Therefore, models of NO_3^- uptake do not need to describe the root system in much detail. But in anaerobic soils, N is largely taken up as NH_4^+ which is adsorbed on soil surfaces and therefore comparatively immobile. Thus, the niceties of root morphology are more important for modelling N uptake by lowland rice.

The simplest mechanistic model of nutrient uptake considers that when crop demand for the nutrient exceeds the sum of the current potential uptake rates of individual roots, the roots behave as zero sinks for the nutrient. This means that the rate of uptake at the root surface is assumed to be so much greater than the rate of transport through the soil that the concentration in the soil solution at the root surface is zero (or some small limiting value) and the transport rate calculated accordingly. But calculations with such a model lead to the conclusion that measured root length densities in lowland rice are greater than necessary to explain measured N uptake rates when no other nutrient is limiting growth. The following three not mutually-exclusive hypotheses may explain this.

Hypothesis 1: *Root length densities are governed by the needs of water uptake, not nutrient uptake*

Superficially this seems unlikely for flooded lowland rice. However, calculations with measured root-surface hydraulic conductivities suggest that root surface areas required for typical transpiration rates in tropical rice are indeed high. But reliable measurements of root hydraulic conductivities are difficult and the differences between published values for different plants and between those for the same plant vary sufficiently that the calculation is not unequivocal. We know of no values for rice.

Hypothesis 2: *The zero sink model is inadequate because the value of the nutrient concentration in the soil solution at the root surface above which uptake is independent of this concentration is significant*

There are also experimental difficulties in testing this hypothesis. The first is to arrange conditions such that transport to the root surface does not limit uptake. This is achieved with rapidly stirred nutrient solutions. Many experiments in the past were flawed by inadequate stirring so that the concentration at the root surface was not the same as that in the bulk solution and uptake rates were limited by transport across the unstirred layer. Therefore the measured uptake rates did not indicate the true root uptake capacity. The test of adequacy of stirring is whether or not further increases in stirring rate further increase uptake.

The next difficulty is that plants are able to regulate uptake rates in accordance with demand so that a fall in the external nutrient concentration may be matched by an increase in the uptake rate per unit root length. If this adjustment is insufficient to meet demand the plant may then allocate more carbon to the root system and so increase root length, or it may increase root length per unit carbon. Thus short-term measurements of the relation between uptake rates per unit root length and external nutrient concentrations — e.g., studies in which uptake rates are gauged from the decline with time in the nutrient concentration in a solution bathing roots when the nutrient is not replenished — are likely to be misleading. Long-term (i.e., over several weeks) steady-state measurements are therefore required with external nutrient concentrations kept constant. These should include uptake rates per unit root length and the effects of internal N status on root:shoot dry wt partitioning and root length:root dry wt partitioning. This is difficult and laborious, and we know of no such measurements for rice; but measurements are currently underway at IRRI.

We will then be able to replace the zero-sink root-surface boundary condition in the nutrient transport model with a relation between the uptake rate per unit root length and the concentration in solution at the root surface. In this model, as long as the concentration at the root surface exceeds the critical value below which the plant cannot further increase uptake per unit root length, potential uptake per unit root length is at a maximal value. Now if net potential uptake by the root system exceeds plant demand, the plant regulates uptake per unit root length so that actual uptake equals demand. But when demand exceeds potential uptake, actual uptake is determined by the extent to which the plant can adjust the root:shoot dry wt ratio (and possibly the root surface area:root dry wt ratio) to match demand, as predicted from a relation between the plant's internal N status — as gauged by some appropriate measure — and the root:shoot partitioning. Then, when the concentration at the root surface falls below the critical value, net uptake depends on both root:shoot partitioning and the relation between uptake and concentration at the root surface. The long-term stirred nutrient solution experiments will also provide information on root:shoot partitioning versus plant internal N status.

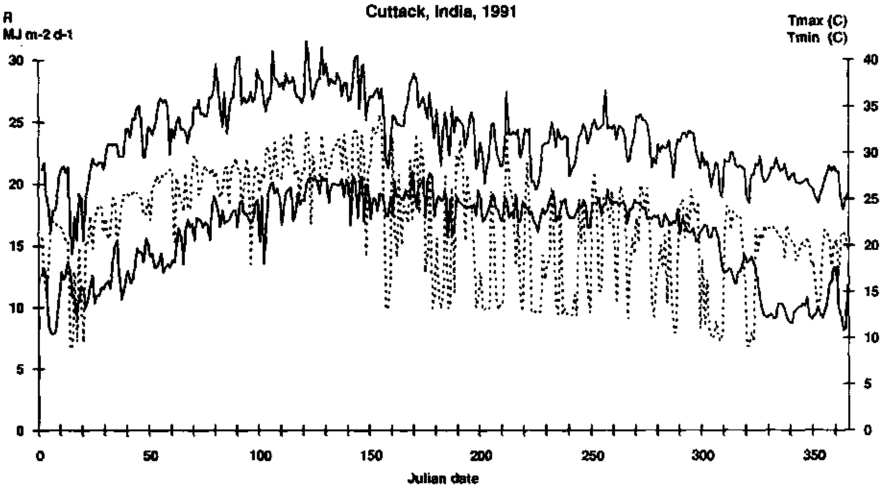
Hypothesis 3: *Root-induced changes in the soil impede N transport to root surfaces*

The simple nutrient uptake models assume that the distribution of the nutrient between the soil solid and solution — and hence its mobility — does not vary between the soil bulk and the root surface. But in theory, root-induced iron oxidation and acidification may greatly reduce the mobility of NH_4^+ near rice roots. The result would be an increase in the root length density required for a given rate of uptake.

Appendix 1. Weather data

The weather data recorded during the experiments at the various sites are presented in this appendix, to enable further interpretation of the experimental data reported in this volume of the SARP Research Proceedings. The following is not a complete compilation, as not all weather data were made available before completion of these proceedings.

One common legend applies to all figures in this appendix: broken lines for global radiation (MJ m^{-2} d^{-1}), solid lines for minimum and maximum temperatures (degrees Celsius). Global radiation was either measured or derived from sunshine duration.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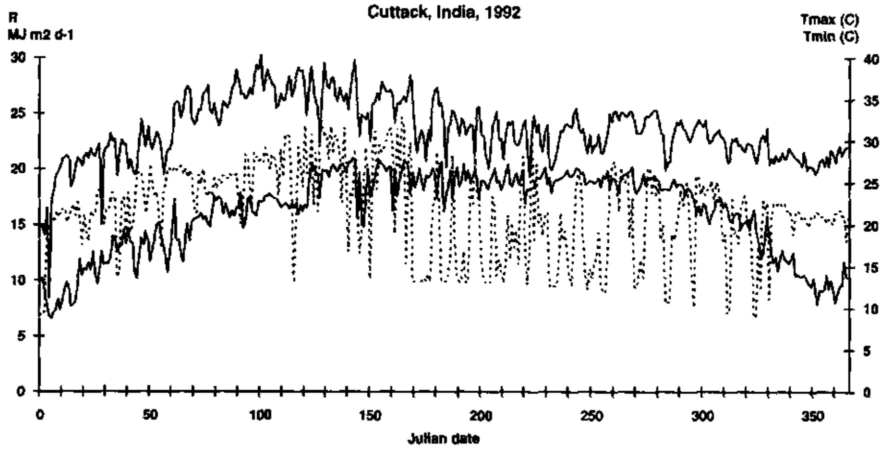
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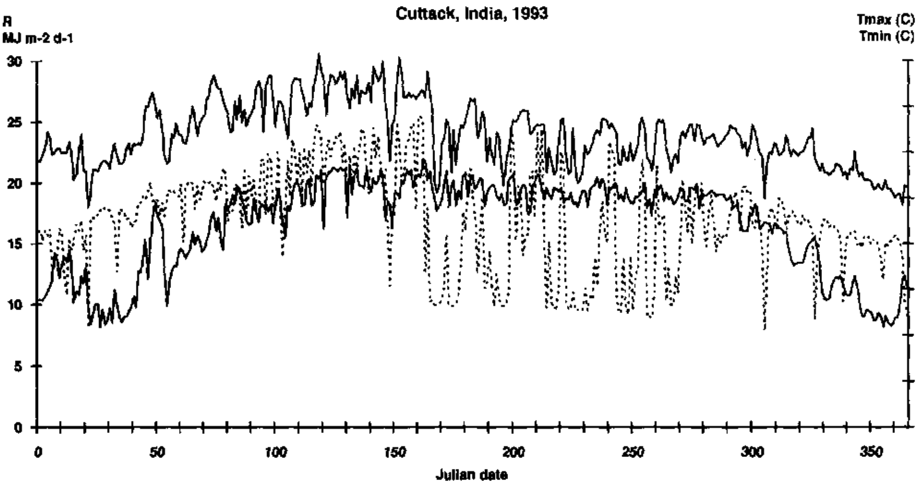
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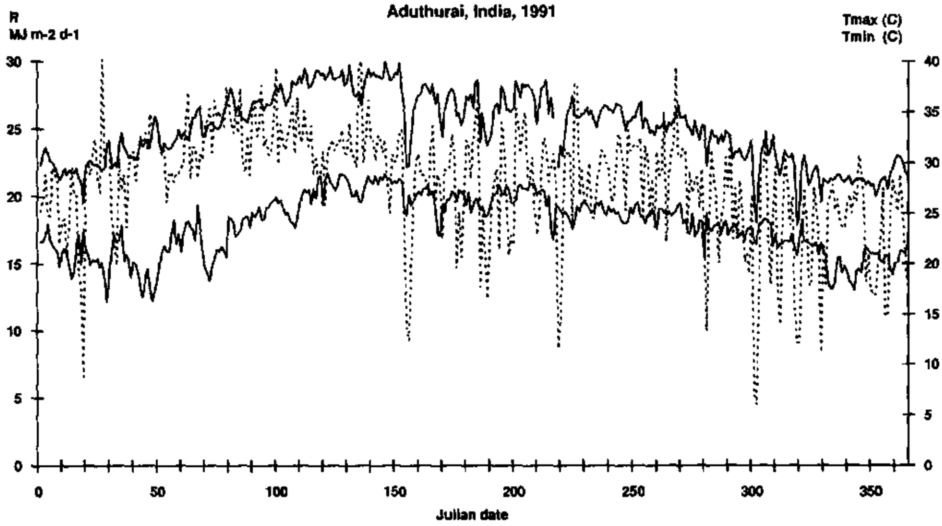
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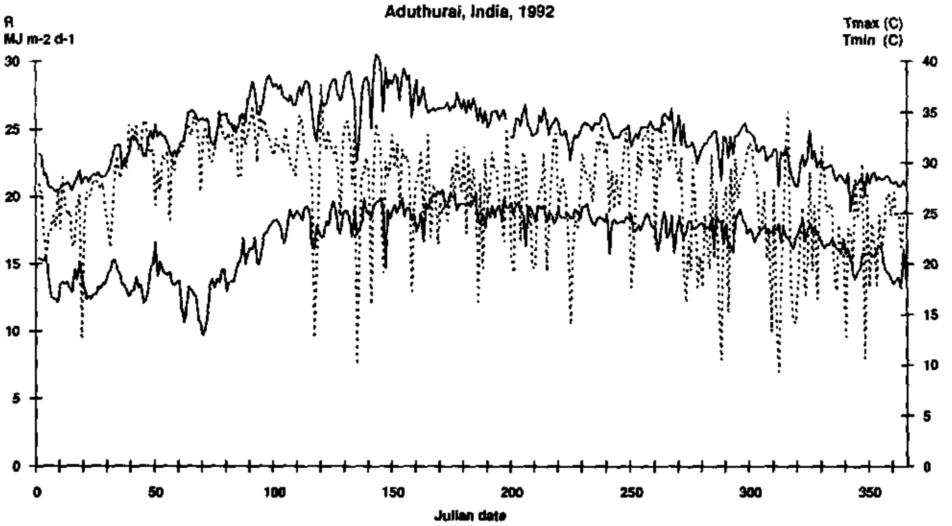
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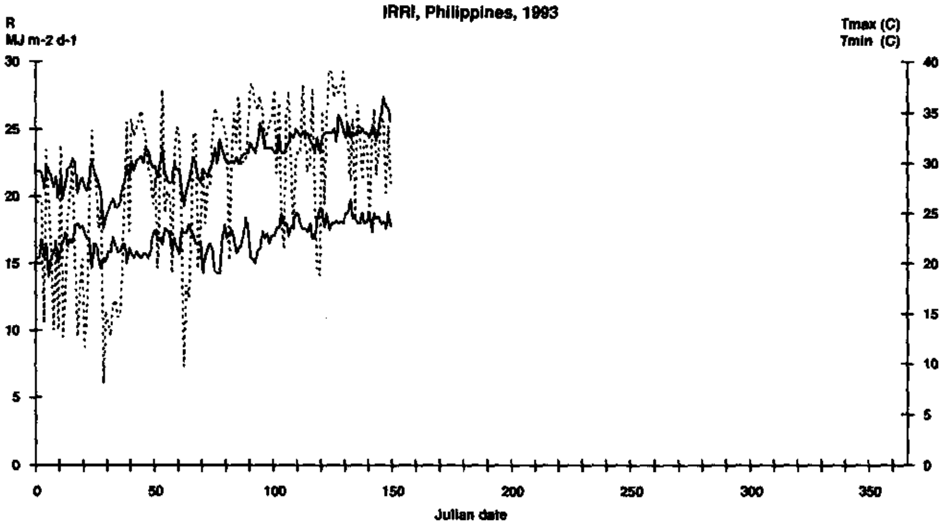
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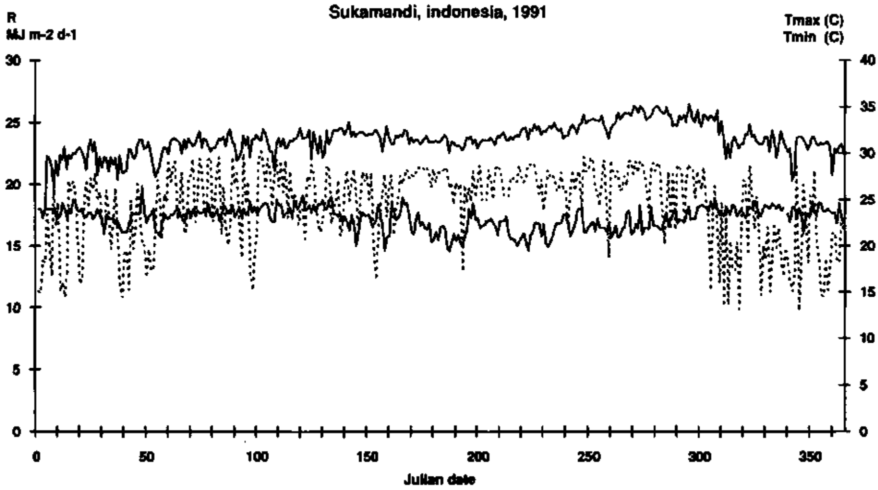
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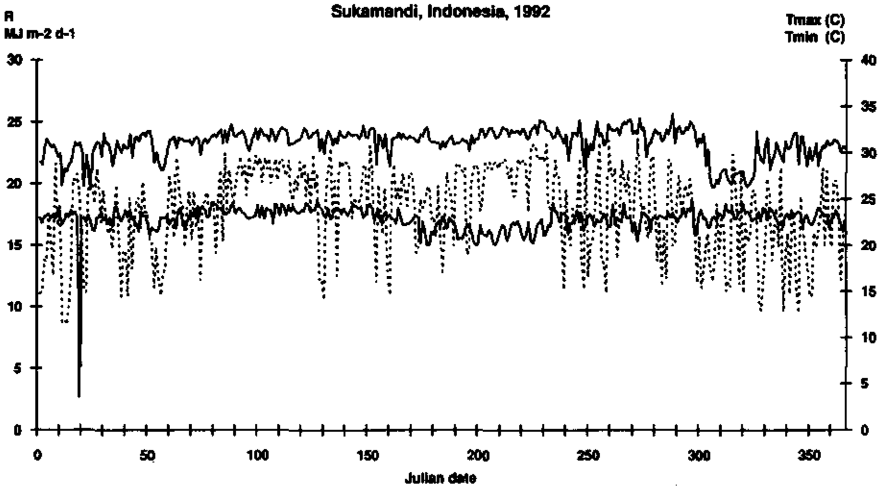
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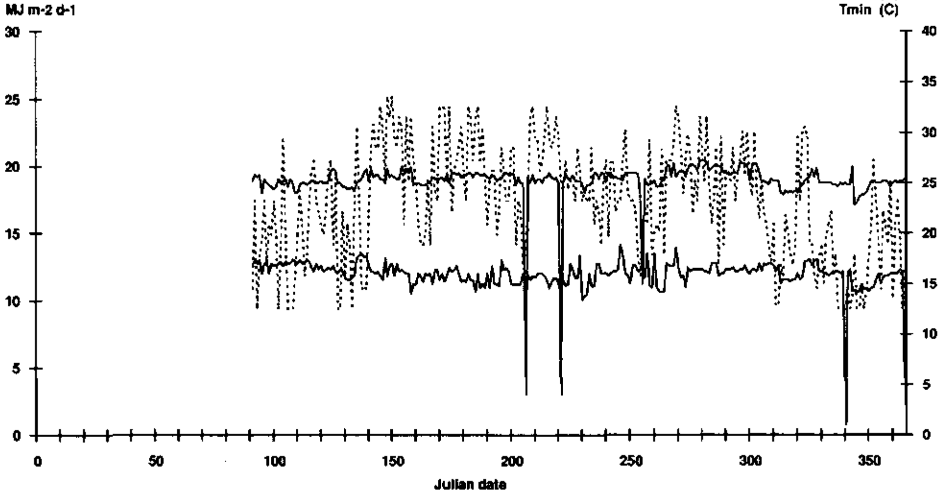
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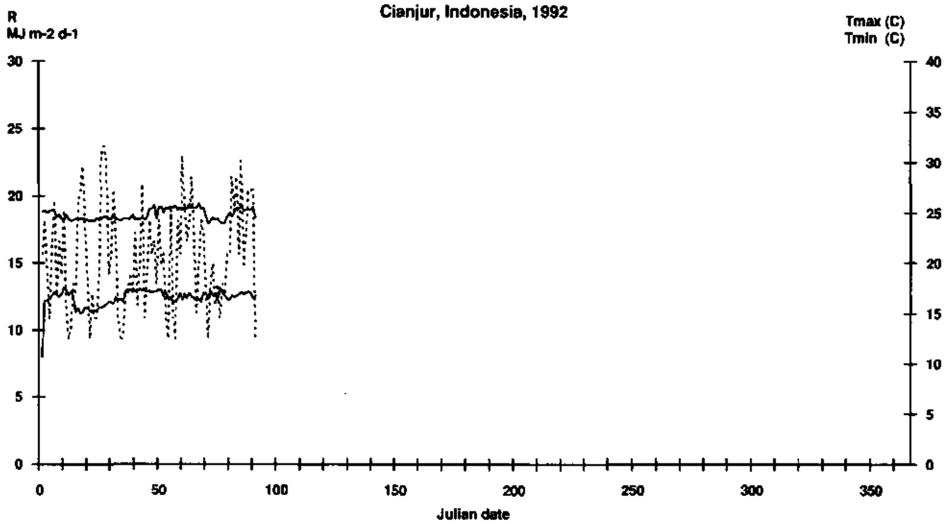
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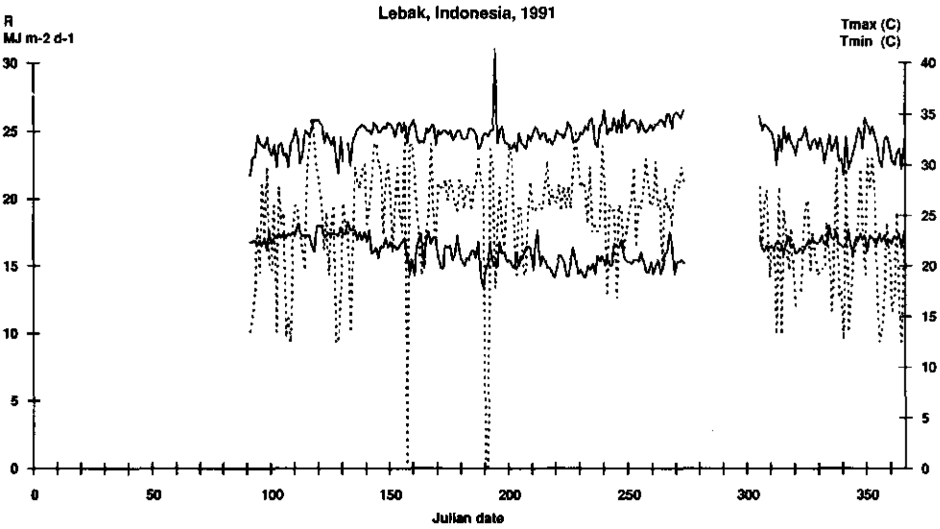
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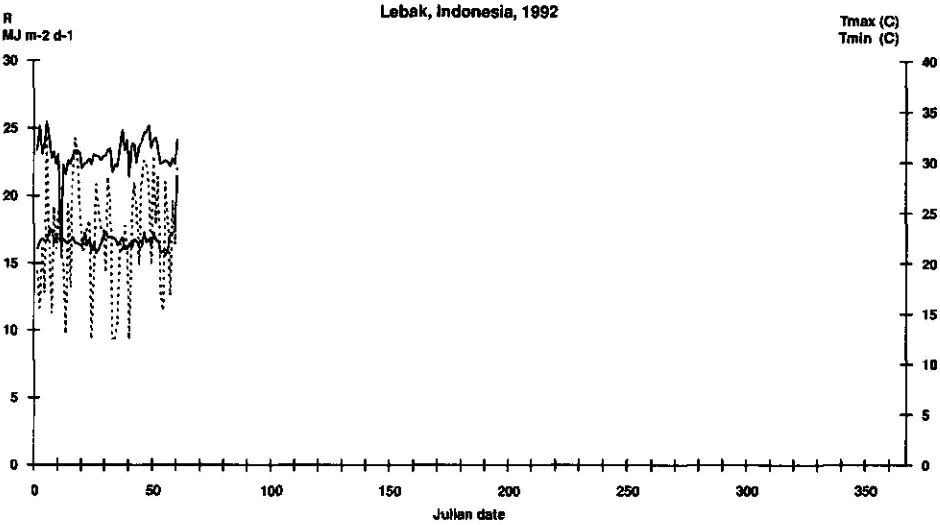
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MJ m-2 d-1
Tmax (C)
Tmin (C)
30
25
20
15
10
5
0
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35
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250
300
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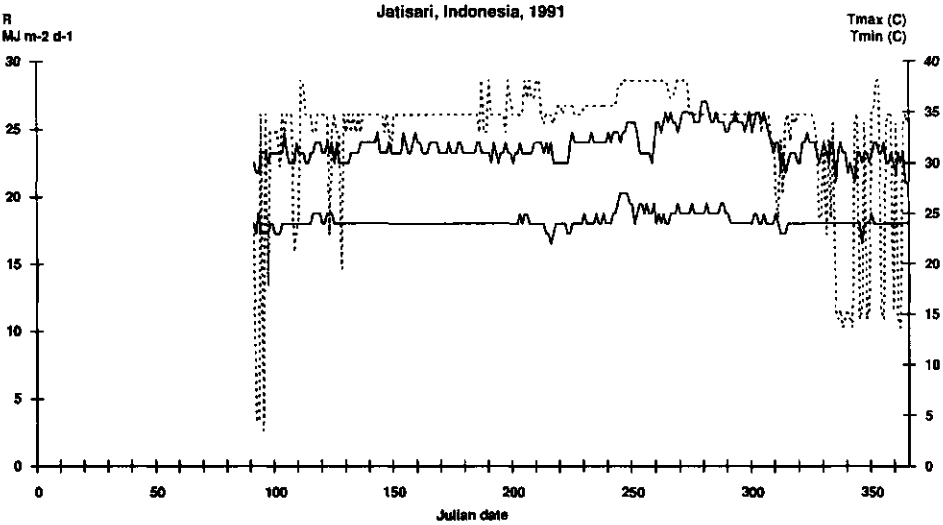
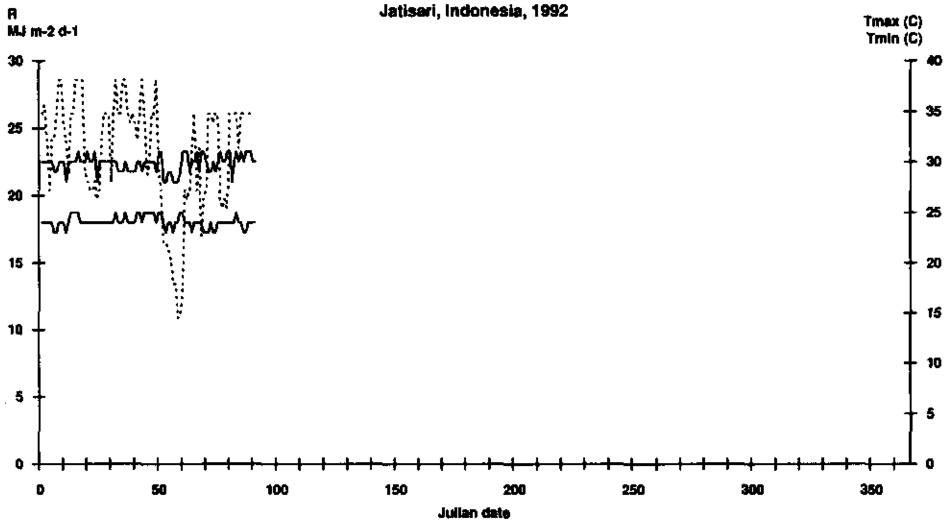
Julian date



Jatisari, Indonesia, 1991



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Appendix 2. List of participants

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