Towards higher nitrogen efficiency in European rice cultivation

A CASE STUDY FOR THE CAMARGUE, SOUTH OF FRANCE

Promotor: dr. ir. R. Rabbinge
hoogleraar in de produktie-ecologie, met bijzondere aandacht voor de plantaardige produktie

Co-promotor: dr. ir. H.F.M. ten Berge
Instituut voor Agrobiologisch en Bodemvruchtbaarheidsonderzoek, Directie Landbouwkundig Onderzoek (AB-DLO).

Towards higher nitrogen efficiency in European rice cultivation

A CASE STUDY FOR THE CAMARGUE, SOUTH OF FRANCE

Nicolaas C. Stutterheim

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The study reported here results from a collaborative research project of the: i) Department of Theoretical Production Ecology, Wageningen Agricultural University, The Netherlands, ii) Research Institute for Agrobiology and Soil Fertility (AB-DLO), Wageningen, The Netherlands, and iii) Laboratoire des Etudes Comparées des Systèmes Agraires (LECSA-INRA), Montpellier, France. Part of the project was financed by the Direction General XII of the European Community through research grant ERBSC1*CT915142.

Cover design: Kyah ter Haar-Romeny

errata corrige

p. 6 Legend Fig. 1.3: replace 'Δ' by '•'

p. 70 Fifth paragraph: delete ', which combine high N recovery with high crop production'

p. 72 Legend Fig. 6.1: replace 'The upper boundary of each area represents high fertile soils, the lower boundary low fertile soils' by 'The upper boundary of each area represents low fertile soils, the lower boundary high fertile soils'

1. Teeltkundige maatregelen uitsluitend gericht op het verhogen van de opname-efficiëntie van kunstmest leiden tot een afname van de bodemvruchtbaarheid.

   Dit proefschrift

2. Extra stikstoftoediening aan rijst met als doel de gevolgen van een te geringe plantdichtheid te compenseren door uitstoeling, is goed voor de boer zijn gemoedsrust, maar niet voor zijn portemonnee.

   Dit proefschrift

3. Voor eenzelfde variëteit is de optimale bladoppervlak dynamiek ter verkrijging van een zo hoog mogelijke rijstopbrengst, per seizoen verschillend.

   Dit proefschrift

4. In de Camargue is - per ha - 100 kg stikstof doorgaans voldoende om 7 ton rijst te produceren.

   Dit proefschrift

5. De basis van een gezond landbouwbedrijf is de organische stof.

   Dit proefschrift

6. Het aanbrengen van windsingels op de agrarische bedrijven in de Camargue zal de boeren geen windeieren opleveren.

7. Met het huidige kennisniveau omtrent het functioneren van de basisprocessen in een gewas, is het gebruik van een of meerdere correctiefaktoren in gewasgroei-modellen onvermijdelijk.

8. Het blinderen van achterruiten van bedrijfsauto's op grijs kenteken, verhoogt het risico op ongelukken. Het verplichten hiertoe, maakt het verkeersveiligheidsbeleid van de overheid ongeloofwaardig.

9. Het heeft geen zin het Nederlands als officiële Europese taal te handhaven.

10. Een dr. titel mag een voordeel zijn bij het opbouwen van een wetenschappelijke carrière, maar gezien de ontwikkelingen op de arbeidsmarkt is het eerder een nadeel.

11. De zorg voor het personeel in een bedrijf is af te meten aan de kwaliteit beeldschermen die er gebruikt worden.

12. 'La patience est la mère de vertu' zei mijn moeder altijd, en gezien dit proefschrift heeft zij gelijk.

Nicolaas C. Stutterheim

Towards higher nitrogen efficiency in European rice cultivation; a case study for the Camargue, South of France

Wageningen, 1 maart 1995

Abstract

Towards higher nitrogen efficiency in European rice cultivation; a case study for the Camargue, South of France (Naar efficiënter gebruik van stikstof in de Europese rijstbouw; een case-studie voor de Camargue, Zuid-Frankrijk) - Stutterheim, N.C., 1994.

This study focuses on an increase in the efficiency of fertilizer nitrogen in irrigated, direct seeded rice. Three indicators for efficiency were used: agronomic efficiency, utilization efficiency and recovery. Experiments were conducted in the Camargue in the South of France, to quantify these indicators for standard non-coated prilled urea under conventional management of irrigated rice. The results were compared to those derived from data originating from other surveys within the Mediterranean rice growing countries. Additionally, the indicator values were experimentally assessed for a resin coated nitrogen fertilizer, known to be highly efficient. Those values were considered to represent the maximum attainable nitrogen efficiencies under given circumstances in the Camargue. A model was developed with which the effect of different nitrogen application strategies on crop production and fertilizer nitrogen recovery can be evaluated. With this model, 70 combinations of quantity and timing of prilled urea nitrogen were screened for 20 sets of weather data, to derive an alternative to the use of the efficient but expensive coated fertilizer. As a result of this simulation, a tailor-made application strategy for a representative medium-growth duration rice variety of the Camargue was defined.

additional key words: environment, fertilizer efficiency, management, modelling, nutrients.

Aan mijn ouders

Preface

Many people have contributed to the research that is described in this thesis. I am very grateful for their support.

The work reported here is the result of a collaborative program of the 'Laboratoire des Etudes Comparées des Systèmes Agraires' (LECSA) of the 'Institute National de la Recherche Agronomique' (INRA) in Montpellier, France, and the Department of Theoretical Production Ecology (TPE) of the Wageningen Agricultural University (WAU) in the Netherlands. This collaboration was started in April 1988. The contribution of the Research Institute for Agrobiology and Soil Fertility (AB-DLO) in Wageningen, permitted to continue the program from July 1990 to obtain the degree of doctor. Additional funding was received from DGXII of the European Community.

The first years of experimental work in the South of France were spent at the LECSA laboratory of dr. A.P. Conesa. Under his guidance, the research group on rice in the Camargue developed into a young and dynamic team, in which it was very stimulating to work. Fred, je te remercie sincèrement pour la hospitalité pendant mes séjours à LECSA. The scientist responsible for the LECSA rice research group was dr. J.M. Barbier. He spent a lot of time helping solving all kinds of problems, ranging from basal questions such as how to arrange for a work permit in France, to more scientific ones, such as how to monitor N dynamics in irrigated rice. He taught me more about rice cultivation than I could have learned from books. Jean-Marc, je te remercie pour toutes tes efforts qui ont attribués à la réalisation de ma thèse. Grâce à toi, j'ai pu profiter d'un temps formidable à Montpellier.

Many French colleagues and friends helped me during my experiments, as well in the Camargue as in the laboratory. I this context I would especially like to thank R. Hammond and B. Nougaredes for their enthusiasm. The quantity of samples to analyze and the long days in the fields did not discourage them, and their contribution was invaluable for the accomplishment of the present study. Furthermore, the social support of J.C. Mouret, J.E. Bergez, F. Bidard and N. Sadurni was great. I thank them and their relatives for the time we spent together.

At Wageningen, my promoter Prof. dr. ir. R. Rabbinge always found time to give valuable comment to the reports and papers I produced. His systematic way of analysis, and his competence to identify the main issue in complicated problems, were a great help in realizing this thesis. Rudy, despite the many activities you have, you always kept the door open for the inevitable problems that came up during my Ph.D.. Your advice, mostly scientific, but sometimes personal, was of major importance in the realisation of this work, I like to thank you for your contribution.

Invaluable was the assistance of Prof. dr. ir. H. van Keulen. He represented for me the main source of knowledge on the topic I treated in my study. His corrections on my drafts obliged me sometimes to reconsider my theories, or to seek for more consistency in my formulations. Herman, I learned a lot from you. Although you were not directly involved in the project, your contribution was of main significance. I sincerely thank you for the invested time and effort.

My co-promoter, dr. ir. H.F.M. ten Berge, guided my research on a weekly basis. His comments and suggestions were of great help for me. Hein, despite the European character of my research, I thankfully made use of assistance, models and data from SARP. I highly appreciate your cooperation and support during my work and I hope that the results presented in this study can contribute to the research within SARP.

The director of AB-DLO, dr. ir. H. Spiertz, kindly gave me the opportunity to realize my thesis at his Institute, while Prof. dr. ir. Penning de Vries, head of the Agro-System Research department of AB-DLO, provided the means to accomplish this thesis. The cooperation of W.P.M. Wolters of WAU and Mr. A. van Peer of Sierrra Chemicals Europe in searching for research funds is appreciated.

Furthermore, I would like to thank all who participated with me in one of the Ph.D. discussion groups of the C.T. de Wit School of Production Ecology. The sometimes lively discussions on different disciplines and the exchange of ideas, enriched my perception of science.

All colleagues of AB, LECSA and TPE who are not explicitly mentioned but attributed in one way or another to my work, are kindly acknowledged.

I express my special thanks to my parents who permitted me to realize my study. I like to dedicate this thesis to them.

I am grateful to Monique for her support during most of the time I spent on this thesis.

Nicolaas Stutterheim
Wageningen, November 1994

Contents

Chapter 1

General introduction

With a world production of 520 Megaton (Mt) rough rice in 1991, an average annual production increase of 1.1% is needed to cover the projected rough rice food demand of 758 Mt in 2025 (IRRI, 1994). Much of that increase is expected to come from irrigated rice because more than 70% of the world rice supply is produced in irrigated ricelands (IRRI, 1989).

Germplasm improvement and intensification[1] seem the most appropriate ways to realize the required growth in rice production because on a world scale the availability of arable land is stabilizing (FAO, 1993). However, intensification may put an undesirable burden on the environment if inputs[2] are lost from agricultural fields. Rice production research, therefore, has to address the question how production can be increased with minimum negative side effects on the environment.

The degree of intensification in rice production varies enormously throughout the world due to the different ways in which rice is cultivated. Main cropping differences exist between upland rice and lowland rice. Lowland rice may be irrigated or rainfed. Under fully irrigated conditions, rice may be transplanted or direct seeded. Direct seeding under irrigation is the most capital-intensive form of cultivation. This makes this type of rice farming most appropriate to consider in studies concerned with input-use efficiency, because of the high losses often associated with high input levels (Van Keulen, 1982).

This thesis is on the improvement of fertilizer nitrogen (N) efficiency in irrigated, direct seeded rice in Europe. Three indicators for N efficiency[3] are used: i) agronomic efficiency, or the amount of N applied per unit grain dry mass, ii) utilization efficiency, i.e. the N uptake per unit grain dry mass, and iii) recovery of applied fertilizer N, which is the fraction of fertilizer N that is taken-up by the crop (kg kg^{-1}). The methodology applied in the study is illustrated for the Camargue, a region comprising the delta of the Rhone river in the South of France. The Camargue represents a typical European rice production area; high radiation

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1 In this text, *intensification* is defined as the increasing use of capital-input (equipment, water, chemicals) per unit area.

2 By *input* capital-input is meant, unless otherwise stated.

3 When the term N efficiency is mentioned in the text, all three efficiency indicators are meant.

levels, abundant water availability, hardly any diseases and pests, and a high degree of mechanisation. In Europe, 404,000 ha rice land is found (FAO, 1993), representing 0.3% of the world's area cropped to rice. European rice production mainly takes place near river deltas of international ecological importance (Directory, 1984), which makes research aiming to improve fertilizer N efficiency, and thus to reduce actual N emissions to these sites, especially relevant.

The context of the study

In 1984, a four year agronomic survey was started by the Laboratory of Agrarian Systems Research (LECSA) of the Institute National de la Recherche Agronomique (INRA) in France. The aim of the survey was to analyze the primary production constraints for rice in the Camargue. An inventory was made of the cultural conditions in the Camargue, i.e. information was acquired on soils, crop rotations, crop characteristics, technical know-how and socio-economical conditions.

A number of 100 fields cropped to rice were monitored in 1984. In the following years, till 1988, 25 fields were selected and followed more intensively. Fields were selected in such a way that a reliable sample of the farms in the region was obtained (Mendez del Villar, 1987). Observations on crop and soil were made on small plots within each of those fields. The acquired information was analyzed using multivariate techniques. For more detailed information on this survey reference is made to Barbier *et al.* (1986) and Mouret (1988).

As the data analysis indicated that the N efficiency in rice cultivation of the Camargue was low, controlled experiments on N management were carried out in 1989 and 1990 (Stutterheim and Barbier, 1994, Stutterheim *et al.*, 1994b). The aim of the experiments was to demonstrate that under the prevailing local circumstances it was technically feasible to increase the fertilizer N efficiency without yield reduction. The data from these experiments were used for the development of a dynamic model on N limited growth of rice. Those activities were carried out for the present study.

Throughout the period 1989 - 1992, demonstration fields were laid out for extension services and farmers.

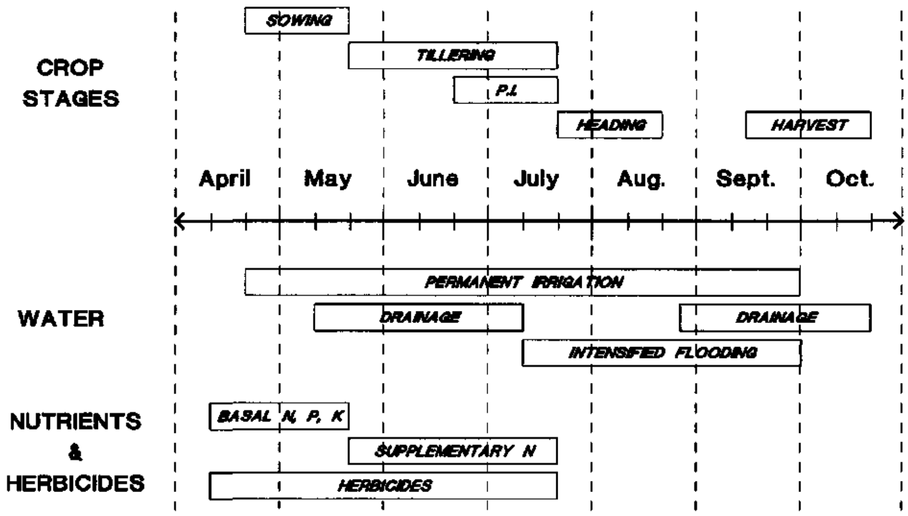

Fig. 1.1 Rice cropping calendar for irrigated rice in the Camargue.

Rice cropping practices in the Camargue

Before sowing of the new rice crop in April or May (Fig. 1.1), the field is ploughed in the autumn and levelled in the spring. After one or more field operations to break-down most of the largest soil clumps, N, P and K fertilizer is applied on top of the dry soil surface and incorporated with a rotary harrow. On average 100 to 120 kg N ha^{-1}, 30 to 90 kg P ha^{-1} and 80 to 120 kg K ha^{-1} is applied as basal dressing. The fertilizer can be in a combined form or in the form of prilled salts. The time between fertilizer incorporation and sowing *cq.* flooding may vary for several reasons: i) to minimize equipment change on the limited number of tractors, fertilizer incorporation and seedbed preparation are carried out on all the fields of the farm before sowing, cq. flooding, is started; ii) constraints in the irrigation system requires that all pre-flood operations on the whole farm are finished. iii) weather (temperature, wind) may cause a delay in sowing and/or flooding (sometimes farmers decide to sow into the floodwater because of the water-temperature being higher than the air-temperature at night). Hence, sowing and flooding may start several weeks after fertilizer application depending on of farm size.

In the Camargue, germination takes place under water, an environment particularly unfavourable for seedling survival. Turbulence in the irrigation water provokes the seeds to be covered by soil. This may, to some extent, be prevented by adapted land preparation and/or measures to increase the stability of the seedbed structure (Barbier *et al.*, 1991). However, with wind velocities up to 100 to 120 km h^{-1} ('Mistral') some seed covering seems unavoidable. In the soil, seeds rapidly experience oxygen shortage which hampers the development of the radicle and nodal roots. Furthermore, the dark surrounding of the emerging plantlets induces extra-ordinary elongation of the mesocotyl, the coleoptile, the first and second leaves, and the first and second internodes (Yoshida, 1981). These young plantlets are poorly embedded in the soil and are easily uprooted by the water movement under windy conditions. As a result, 50 to 70% of the applied seed is normally lost in rice fields of the Camargue.

In the period up to tillering, farmers repeatedly drain their fields (Fig. 1.1) mainly to increase the effects of contact herbicides. This practice has the advantage of increasing the oxygen supply to the soil and thus to promote plant establishment. Crop growth may profit from re-oxygenation of the soil. Following flooding, the soil rapidly decreases in redox-potential (Fig. 1.2), which affects root quality (Matsushima, 1979). In the Camargue, a large proportion of roots may have degenerated around the beginning of July, corresponding to the end of tillering *cq.* panicle initiation (Fig. 1.1). Soil re-oxygenation is most effective on heavy soils high in organic matter content, because reduction processes are intense in such soils (Fig. 1.2).

At tillering and around panicle initiation additional N may be applied (Fig. 1.1) in quantities ranging from 30 to 50 kg N ha^{-1} per application. Contrary to the basal application this fertilizer is spread into the standing floodwater. Herbicides are frequently applied during the vegetative growth phase.

From the start of panicle initiation till harvest, farmers merely have to control the water level of their fields. The level is increased from 10-15 cm to 25-30 cm just before flowering (Fig. 1.1), to protect the plants against the negative effects of strong fluctuations in temperature. A few weeks before harvest, drainage takes place to facilitate harvest operations.

The efficiency of N fertilizers applied to rice in the Camargue

Application and incorporation of N fertilizer to the dry soil just before irrigation seems theoretically an appropriate technique to reduce losses of N by processes like ammonia-volatilization, nitrification-denitrification and horizontal run-off. However, as noticed already, the farmer may have practical difficulties to irrigate soon after the incorporation of the

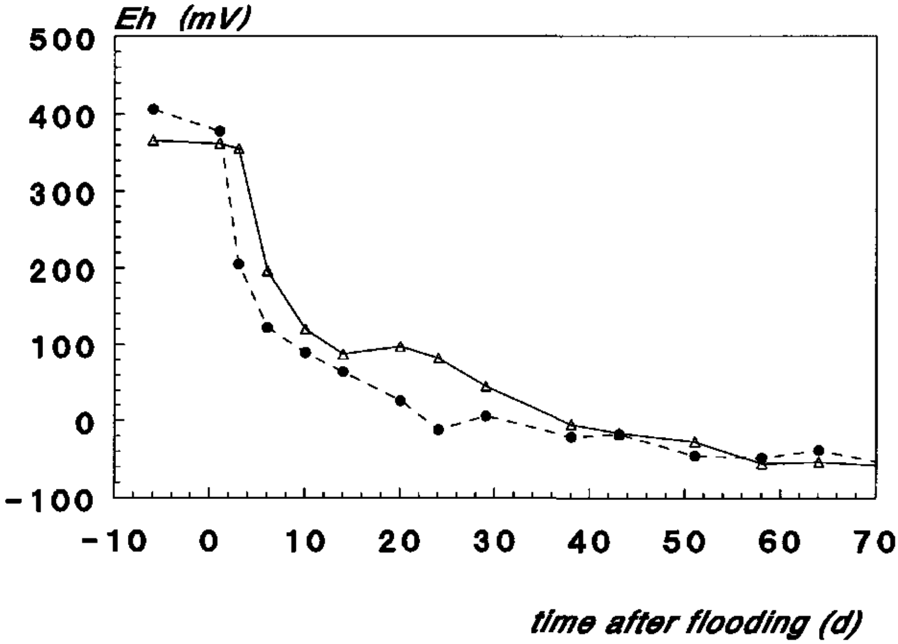

Fig. 1.2 Redox-potential of a soil surface layer (0.05 m) through time. A soil volume of 0.03 m^3 was continuously covered with irrigation water of 0.15 m depth in containers cropped to rice cv. Cigalon. ▵ = silt loam soil. • = silty clay loam soil.

fertilizer. In this lag-period, strictly aerobic nitrifying bacteria convert the fertilizer ammonium into nitrates (nitrification). The rate of nitrification mainly depends on the amount of organic carbon, soil aeration and temperature (Watanabe *et al.*, 1981; Schmidt, 1982). As soon as irrigation starts, nitrates rapidly disappear from the soil (Fig. 1.3) by lateral flushing, leaching, or denitrification in the increasingly anaerobic soil. This process of nitrification-denitrification may be repeated with re-oxygenation of the soil. Hence, although drainage practices may be good for crop establishment and further plant growth, it highly increases the risk of N loss.

With fertilizer application into the floodwater, the granules of the fertilizer will end up in the mud layer that forms the transition between the irrigation water and the soil. This N may be taken up by the fine, highly branched roots growing in this transition zone (Yoshida, 1981), but it also may be lost by the chemical and physical processes already mentioned. As the rate of uptake and loss are related to the N concentration, N uptake needs to proceed as fast as possible to limit N loss.

Without any application of N, rice yields of 4 to 6 t ha^{-1} are obtained in the Camargue. This is due to the high natural fertility of the soils of fluvial origin. In the 100 fields that were followed in 1984, 53 fields had a soil organic matter content between 1.6 and 2.5%. Yield is positively related to organic matter content of the soil (Barbier and Mouret, 1992), probably because of an increasing supply of N by immobilization-remineralization at higher soil organic matter levels.

From the survey data, only a very weak relationship could be established between grain yield and fertilizer N management; yields hardly seemed to depend either on the quantity of N input, or on the methods of application. This is reflected in the low value (11 - 13 kg kg^{-1}) of the agronomic efficiency (Barbier *et al.*, 1989). For irrigated rice, these figures can be considered as very low.

It is concluded that the efficiency of N fertilizer may be determined by several processes, which need to be quantified to optimize the use of N fertilizer for crop production. Subsequently, an optimal fertilizer N strategy may be derived.

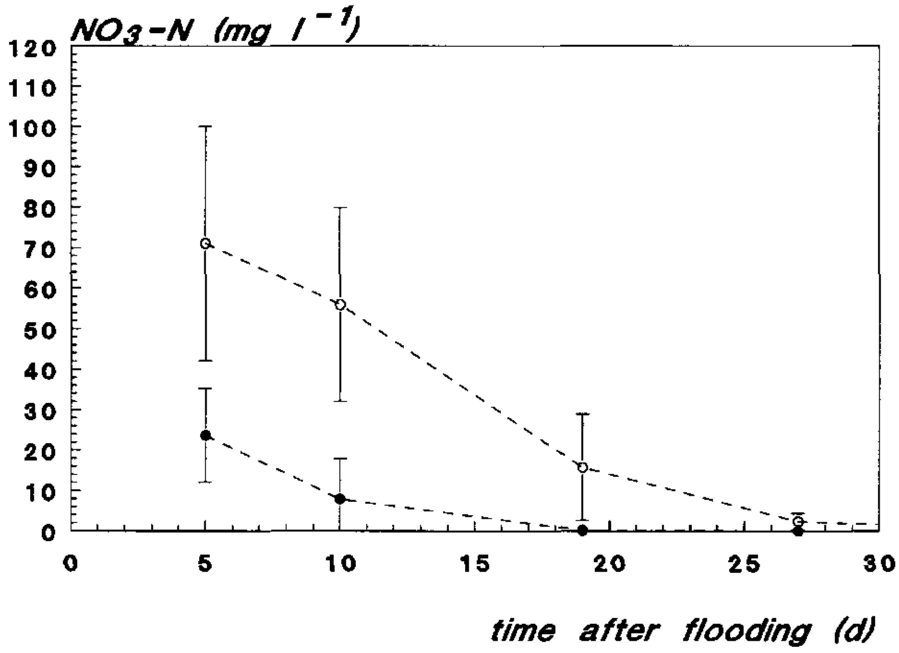

Fig. 1.3 Dynamics of nitrate concentration in soil solution after the onset of flooding of fields in the Camargue that were cropped to rice cv. Lido in 1989. ∘ = loam soil. ▲ = silt loam soil. Bars indicate the standard deviation of the mean.

Research objectives and approach

The main objectives of the present study were: i) to assess the actual and attainable N efficiency of irrigated, direct seeded rice in the Camargue and comparable production areas in Europe, ii) to develop a methodology to derive the optimum application strategy for N fertilizer under various environmental circumstances, and iii) to provide a tailor made N application strategy for a representative medium growth duration rice variety of the Camargue.

Data from the French research program were used to assess the N efficiencies for the Camargue region, while data from European experiments on rice served to do the same for the main rice growing areas on the continent. The results of on-farm experimental research during two years permitted analysis of the N efficiency under contrasting N management. These analyses are presented in Chapter 2.

Measurements on crop and plant level made in both experiments were used to obtain more insight into the growth and yield formation of direct seeded rice in the Camargue. Special attention was given to the role of N in the formation of sink and source capacity of the crops (Chapter 3) to deduce how N may affect yield.

Use was made of dynamic crop growth modelling to derive the optimum N application strategy. By using a model, the effect of different N management practices on growth or N efficiency can be analyzed without numerous field experiments. The management practices found to be promising, can subsequently be tested under field conditions. Several explanatory models on N limited growth of rice exist with a high degree of complexity (c.f. Kropff *et al.*, 1993; Godwin *et al.*, 1990). This makes such models suitable for research, but for use by extension services more simple summary models are required. As extension of research results was one of the primary objectives in the French research program, such a simple model was developed (Chapter 4 and 5).

In Chapter 4, the model NGROW-RICE is presented. It can be used to interpret treatment effects in fertilizer N trials. Main inputs are daily global radiation and the course of crop N through time.

With NGROW-RICE, N management can be evaluated, but only when the N status of a crop is provided. N uptake in dependence of the N level in the soil needs to be mimicked to analyze N management without previous knowledge on crop N status. This was realized by combining NGROW-RICE and the model ORYZA_0 (Ten Berge *et al.*, 1994) into a model called NGROW-ORYZA (Chapter 5). With this model, the optimal application of N was calculated for two cases: the potential case where it is assumed that N can be applied continuously, and the actual case where application of N is at distinct moments during the growth of the crop. Finally, a tailor-made N management advice is formulated on the basis of the results of the study.

Chapter 2

The efficiency of fertilizer nitrogen in irrigated, direct seeded rice (*O. sativa L.*) in Europe.

Abstract Data from 35 experiments with direct seeded rice, performed between 1981 and 1991 by national research institutes in five major rice growing countries of Europe were analyzed to estimate the average efficiency of fertilizer nitrogen (N). Pooled data from a four year regional survey (1984-1988) on rice-based farming systems in the Camargue-region (43°30'-43°40' N) in the south of France, were used to perform a similar analysis. Experimentation during two years (1989-1990) was carried out to assess the value of the N utilization efficiency within the range of N limited growth and to obtain information on the N efficiency under controlled conditions. At reduced basal dressing of N on soils with high soil organic matter content the maximum apparent N recovery was estimated at 0.21 to 0.32 kg N uptake per kg N applied. Maximum agronomic efficiency ranged from 12 to 17 kg grain dry mass per kg N applied. High basal N application on these soils resulted in yield loss. No consistent yield response to fertilizer N input was found on soils with less than two percent organic matter, irrespective of fertilizer timing. These results confirm the important role of soil organic matter in rice cultivation. An average apparent N recovery of 0.18 was obtained with split application of N under controlled experimental conditions in the Camargue. Using a controlled release fertilizer values of 0.58 and 32 kg kg^{-1} were obtained for the apparent N recovery and agronomic efficiency, respectively. Hence, disregarding the economic feasibility, considerable scope exists for improving N efficiency in European rice cultivation.

Introduction

The apparent nitrogen (N) recovery (ANR in kg kg^{-1}) is defined as the ratio of additional N uptake (kg ha^{-1}) in response to fertilizer N application to the amount of fertilizer N applied (kg ha^{-1}). In irrigated rice, ANR normally ranges from 0.2 to 0.4 (De Datta, 1981; De Datta *et al.*, 1983; Vlek and Byrnes, 1986). To increase ANR, extensive research has been carried out during the last decades on alternative application methods and different fertilizer forms (Tejeda *et al.*, 1980; Kolhe and Mittra, 1987; Rao, 1987) resulting in several methods to improve fertilizer N recovery in irrigated rice.

Placement of N in reduced soil layers (deep placement) is very effective in increasing the N recovery (Craswell *et al.*, 1981; Cao *et al.*, 1984). Under anaerobic conditions nitrification strongly decreases with soil depth (Schmidt, 1982), thus reducing N loss by denitrification and leaching (Bilal *et al.*, 1979; Singh and Singh, 1988). Furthermore, deep placement is an effective way to prevent the movement of ammonium (NH_4^+) to the floodwater. Hence, also N losses by ammonia (NH_3) volatilization, run-off and nitrification-denitrification processes are reduced (Craswell and Vlek, 1979; Savant and De Datta, 1982).

Split application is another method that can increase N recovery. Synchronization of nitrogen supply and crop N demand reduces the residence time of the nutrient in the soil environment and hence the fraction of fertilizer N subject to loss.

N recovery can also be improved by using alternative fertilizer forms. Many results (Wells and Shockley, 1975; Rao, 1987; Singh and Katyal, 1987; Chauhan and Mishra, 1989) have shown that the use of coated fertilizers and/or chemical additives can reduce N losses and therefore improve N recovery. Coating creates a barrier between the fertilizer granule and the soil, thus reducing the contact time and contact area between soil environment and the nutrient. Additionally, specific chemical compounds can be added to slow down or inhibit nitrification and as a consequence the loss of N by denitrification.

One group of coated fertilizers are the plastic resin or polymer coated controlled release fertilizers (CRF's) with brand names as Osmocote, Ceracoat, Nutricote and LP-Cote (Fujii and Yazawa, 1989; Fujita *et al.*, 1989). Their coatings are very regular and of constant and controlled thickness (Oertli, 1980). Release of the internal nutrient is by diffusion and its temperature dependence can be altered by adaptation of coating properties (Fujii and Yazawa, 1989; Fujita *et al.*, 1989). Theoretically, the use of CRF's could reduce the need for fertilizer application to a single basal dressing without increasing the risk of fertilizer loss. This already has been illustrated for sulphur coated urea (Flinn *et al.*, 1984; Rana *et al.*, 1984), but field data confirming this for CRF's in rice are lacking.

Literature offers little information on N recovery in European rice cultivation despite the well documented fact that recovery is poor in tropical rice systems. The aim of this contribution is to quantify N recovery for rice in the European situation. Subsequent research can be focused on the quantification of N turnover, and N loss processes in irrigated soils. The latter may be especially important since most rice production areas in Europe are situated near wetland of international importance such as the Tejo Estuaria and Ria Sado in Portugal, the Ebro Delta, La Albufera de Valencia and the Marismas del Guadalquivir in Spain, the Camargue in France, and the area around Ferrara and Ravenna and the Po Delta in Italy (Directory, 1984).

In this paper the average N efficiency is quantified in terms of ANR, the nitrogen utilization efficiency (NUE, in kg grain dry mass per kg N uptake) and the agronomic efficiency (AEFF, in kg grain dry mass per kg N applied). Data from two surveys are used, one covering several European countries and the other focusing on the Camargue region in the south of France. The scope for improvement of N efficiency in rice cultivation is discussed and the importance of soil organic matter (SOM) content and timing of N is demonstrated. To obtain key parameters required for analysing the Europe and Camargue survey data, two detailed experiments were conducted which are discussed first.

Materials and methods

Camargue experiment 1989

Four N treatments were laid out in triplicate using a randomized complete block design (Table 2.1). The control treatment (N0) received no fertilizer N. In N1, 160 kg N ha^{-1} as coated CRF 'Osmocote 40-0-0', a so-called 'three-month-type', was applied as a basal dressing only. Under controlled laboratory conditions, this type of CRF releases N during three months at soil temperatures of 25°C (Sierra Chemical Europe factory specifications). In the other two treatments (N2 and N3) a total amount of 160 kg N ha^{-1} per treatment was applied as prilled urea in different fractions. N2 received two split application in equal fractions of 80 kg ha^{-1} at the three leaf stage (34 days after sowing (DAS)) and near neck-node initiation (56 DAS), respectively. In N3, a basal application of 80 kg ha^{-1} was followed by two splits of 40 kg ha^{-1} at 34 and 56 DAS, respectively. All basally applied N was broadcast and incorporated into the dry upper five cm of the soil together with a combined fertilizer containing P_2O_5 (34.9 kg P ha^{-1}) and K_2O (124.5 kg K ha^{-1}). The medium duration rice variety 'Lido' (medium grain type, spp. *japonica*) was broadcast seeded on the 28th of April, two days after fertilizer application. The next day the field was flooded. It remained flooded throughout the experiment until 142 DAS.

At maturity (142 DAS), four randomly selected areas of 0.25 x 0.25 m were sampled within each plot. After threshing and weighing grain and straw in each sample, subsamples were dried at 80°C during 24 h. Dried material was analyzed for total N according to the improved Kjeldahl-method (Method, 1984).

Camargue experiment 1990

In 1990, a four-level single factor randomized complete block design with three replicates was used to establish the NUE and the optimal dose of Osmocote with respect to AEFF and ANR. Broadcasting and incorporation of Osmocote 40-0-0 at N levels of 0 (N0), 50 (N50), 100

(N100) and 150 kg ha^{-1} (N150) and 34.9 kg P ha^{-1} and 124.5 kg K ha^{-1} as combined fertilizer containing P_2O_5 and K_2O, took place two days before broadcast sowing (11th of Mai) and subsequent flooding (1 DAS). Soil characteristics of the experimental field are presented in Table 2.1. The crop was harvested at maturity, 131 DAS. Management practices, variety, sampling techniques and analyses were identical to those in 1989.

The Camargue survey

Data from a four-year regional survey (1984-1988) on rice-based farming systems in the 'Camargue'-region (43°30'-43°40' N) in the South of France (Barbier *et al.*, 1990) were pooled to analyze the N efficiency in rice on a regional scale. A total of 169 sites, each subjected to different N management (form, quantity and timing), crop and soil management, and weather, were analyzed. Data on yields and N management were obtained from farmer interviews resulting in a data-set of high variability. In view of the likely inaccuracy of the farmer-supplied data, N application was subdivided in classes of width 25 kg N ha^{-1}.

Table 2.1 Characteristics of the experiments carried out in the south of France in 1989 and 1990. The numbers following each N treatment give the amount of N applied in kg ha^{-1} before sowing, at the three-leaf stage and around neck node differentiation, respectively.

EXPERIMENT	SOIL TYPE AND TEXTURE	SOIL ANALYSES	TREATMENTS
EXP89 sowing : 28/4 harvest: 17/9	Silt Loam (SL) (27,70, 3)*	Org. C: 2.5 % Tot. N: 0.24% OM : 4.1 % CEC : 10 meq/100g pHw : 7.9	N0 : 0-0-0 N1 : 160-0-0 as CRF N2 : 0-80-80 as PU N3 : 80-40-40 as PU
EXP90 sowing : 11/5 harvest: 19/9	Loamy Sand (LS) (7, 8,85)*	Org. C: 0.8 % Tot. N: 0.07% OM : 1.4 % CEC : 3.3 meq/100g pHw : 8.1	N0 : 0-0-0 N50 : 50-0-0 as CRF N100: 100-0-0 as CRF N150: 150-0-0 as CRF

()* is percentage clay, silt and sand, respectively. Org. C. = soil organic carbon, Tot. N = total soil nitrogen, OM = organic matter, CEC = cation exchange capacity of the soil, pHw = pH-water. PU = prilled urea, CRF = controlled release fertilizer.

Data were also grouped according to soil type (SOM) and N application strategy (timing). Organic matter classes were: SOM less than 2%, 2-3%, and SOM exceeding 3%. This classification was derived from a logarithmic relation between yield and SOM-content reported for the Camargue (Barbier and Mouret, 1992). Timing of N application was accounted for by distinguishing three subgroups according to the ratio between amounts of basally to total applied N. This ratio represents the relative importance of the basal dressing. The subgroups were: a ratio less than 50% (N mostly applied in splits (NSPL)), a ratio of 50 to 65% (an approximately balanced N application with respect to timing (NBL)), or finally, a ratio above 65% (mainly basal dressing of N (NBAS)).

Yield and N application were related for each combination of SOM and N timing by plotting average yields against average amounts of applied N per application class (e.g. Fig. 2.3a). Standard errors were calculated, both for the yield-average per class and for the average amount of applied N per class.

The Europe survey

The Europe survey consisted of an evaluation of data coming from 35 experiments on direct seeded rice performed between 1981 and 1991 by national research institutes in five major rice growing countries of Europe (Cereal Institute in Thermi-Thessaloniki (Greece); Instituta Agricultura in Milano (Italy); Istituto Sperimentale Cerealicoltura in Vercelli (Italy); Institut National Investigacion Agrarias in Figueira da Foz (Portugal); Instituto Valenciano de Investigaciones Agrarias in Valencia (Spain); Institut de Recerca i Tecnologia Agroalimentàries in Tarragona (Spain); Centro de Investigación y Desarrollo Agrario in Sevilla (Spain) and Thrace Agricultural Research Institute in Edirne (Turkey)). In the experiments, different levels of N application existed and all N was applied basally. Furthermore, between the experiments crop and soil management, site, and year of cultivation differed. The data of all experiments were pooled and sorted according to grain yield and N application level. For all experiments where an identical amount of N was applied the average yield was calculated.

Analysis

Results are presented in a so-called three quadrant format (De Wit, 1953) which combines three curves in one figure. One curve represents grain yield against N application (yield-application curve). Another curve represents yield against N uptake (yield-uptake curve). The third curve relates N application with N uptake (application-uptake curve). Only two out of these three relations are mutually independent; the third relation can always be derived from any two of the three relations. The slopes of the curves represent AEFF, NUE and ANR, respectively.

NUE could not be estimated directly from the survey data because no N uptake was measured within the surveys. Therefore, the results of both 1989 and 1990 Camargue experiments were used to assess NUE. The resulting average value of NUE was subsequently used in analysing the Camargue and Europe survey data sets, thus assuming that NUE is constant across the locations covered by the surveys. According to Van Keulen (1977, 1982) NUE is approximately constant if N is the only limiting factor for growth. For this reason, yield decline at increasing N application, where factors other than N shortage (e.g. pests and diseases, lodging) are obviously limiting production, are not considered in our analysis of N efficiencies.

Yield-application curves were constructed using measured data from each experiment or survey. Subsequently, each yield-application curve was combined with the generalized NUE value obtained from EXP89 and EXP90 to assess the application-uptake curve (according dotted lines in Fig. 2.1 to 2.5). The range in which the linear part of the yield-uptake curve can be used for analysis is determined by the form of the measured yield-application curve. As explained before, only the part of the curve with a positive yield reaction on N input is taken into account in the analysis. Therefore, application-uptake curves in Fig. 2.3, 2.4 and 2.5 can not be extended to the maximum application level of N. The intercept of the application-uptake curve with the uptake axis represents the natural N fertility of the soil, the slope with respect to the application axis represents ANR.

Results

The Camargue experiments 1989 and 1990

The yield-application curve

In every treatment (except N0) of EXP89 the total quantity of applied N was 160 kg ha^{-1}, which resulted in hardly any yield difference (Fig. 2.1). For this reason, no AEFF was calculated for this experiment.

Yields in EXP90 increased up to N applications of 100 kg ha^{-1}. Application in excess of 100 kg N ha^{-1} hardly raised yields above the level of 7285 kg ha^{-1} obtained with N100. On the basis of latter results AEFF was estimated at 32 kg kg^{-1}.

The yield-uptake curve

NUE was determined as the slope of the yield-uptake relations of EXP89 and EXP90 (Fig. 2.1b and 2.2b). Because all other growth conditions were kept optimal as possible while only N availability varied, the slope of the linear part of the curves can be considered as the constant NUE valid under N limited growth conditions.

In EXP89, average N uptake in N2 and N3, both treatments in which N was split-applied, was alike (125 kg ha^{-1}) but clearly lower than that obtained with N1 (158 kg ha^{-1}). This additional N uptake of 33 kg N ha^{-1} under N1 did not result in significantly higher yields. By considering the average yield of 5305 kg ha^{-1} obtained at N0, a yield-uptake curve was constructed with a slope, or NUE, of 55 kg kg^{-1} (Fig. 2.1b).

Maximum grain yields in EXP90 were higher than those in EXP89. This may be attributed to the relatively low temperatures in the first 20 days of grain filling in 1990 (data not presented). Despite this, the yield obtained with N0 in EXP90 was lower than that measured in EXP89 at the same treatment. This indicates that the N supply from natural sources was lower in EXP90. The NUE estimated at 56 kg kg^{-1} was valid up to a N uptake of 120 to 130 kg ha^{-1} (Fig. 2.2b).

Both values of NUE were within the range of 53 to 63 kg kg^{-1} referred to in literature (Van Keulen, 1977; Wada *et al.*, 1986). Hence, in analysing the survey data, the yield-uptake relation was represented by a straight line with an average slope of 56 kg kg^{-1}. The validity of this relation is restricted to a range of N uptake from 0 to near 120 kg N ha^{-1} (Fig. 2.1b and 2.2b).

The application-uptake curve

Two separate application-uptake curves were constructed from the data of EXP89 (Fig. 2.1c), demonstrating a change in recovery fraction of fertilizer N due to the different N treatments. One curve related a N uptake of 125 kg N ha^{-1} in N2 and N3 with the application of 160 kg N ha^{-1}; the other curve related a N uptake of 158 kg N ha^{-1} in N1 with 160 kg N ha^{-1} applied. In this way ANR values of 0.18 and 0.38 were established for N2/N3 and N1, respectively.

The application-uptake relation for EXP90 is given in Fig. 2.2c. Average ANR of fertilizer decreased significantly at application rates exceeding 100 kg N ha^{-1} or an uptake of 133 kg N ha^{-1}. At application rates below 100 kg N ha^{-1} the average ANR was 0.58 kg kg^{-1} while any applied N above that level, up to 150 kg ha^{-1}, was only for 12% recovered.

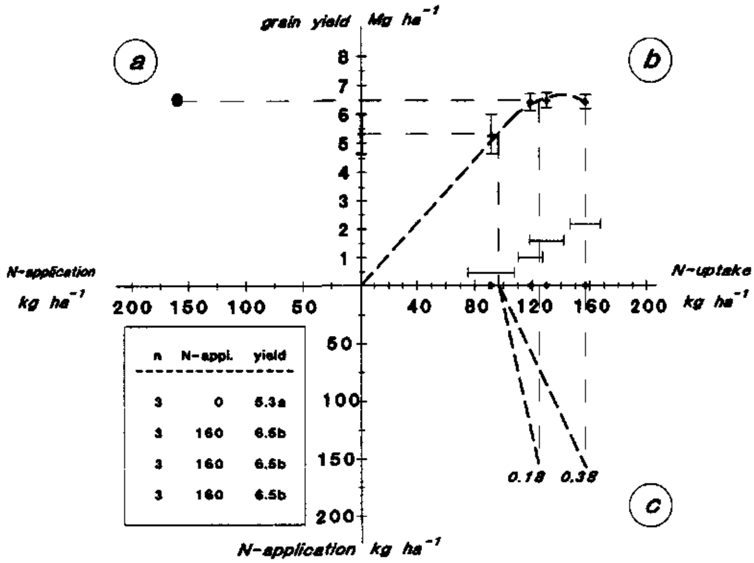

Fig. 2.1 The yield-application curve (a), the yield-uptake curve (b) and the application-uptake curve (c) for the Camargue-experiment in 1989. Vertical and horizontal bars indicate standard errors of yield and N-uptake estimates, respectively. The numbers beneath the application-uptake curves represent the mean apparent nitrogen recovery fraction for prilled urea (left) and for controlled release urea as Osmocote (right). Tabulated values of measurements used in quadrant a) are given, together with the number of observations used for statistical analysis. Yields with different letters vary significantly at the 5% level.

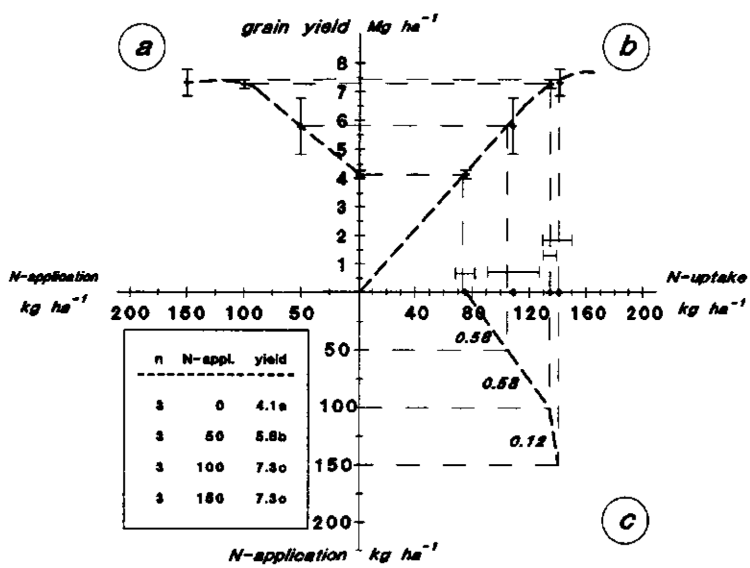

Fig. 2.2 As Fig. 2.1 but this time for the Camargue-experiment with controlled release fertilizer in 1990. Numbers left of the application-uptake curve are apparent nitrogen recoveries calculated for each increment in applied fertilizer-N.

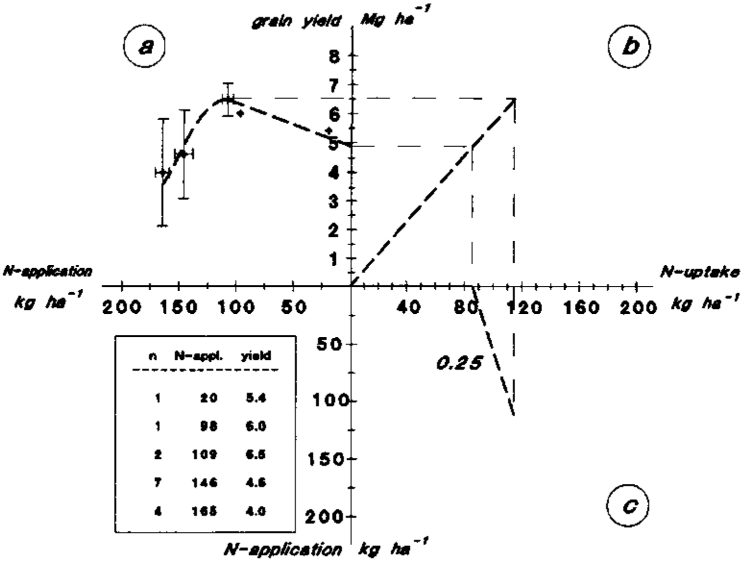

Fig. 2.3 The three quadrant Figure for soils of the Camargue-survey containing more than 3% SOM and receiving NBAS (see text). Vertical bars indicate standard errors of yield estimates, horizontal bars represent standard errors of N-application estimates per application class (see text). Left of the application-uptake curve the mean apparent nitrogen recovery is given. Average values of applied N and yields, used to construct quadrant a), are indicated, together with the number of observations used to calculate application and yield averages.

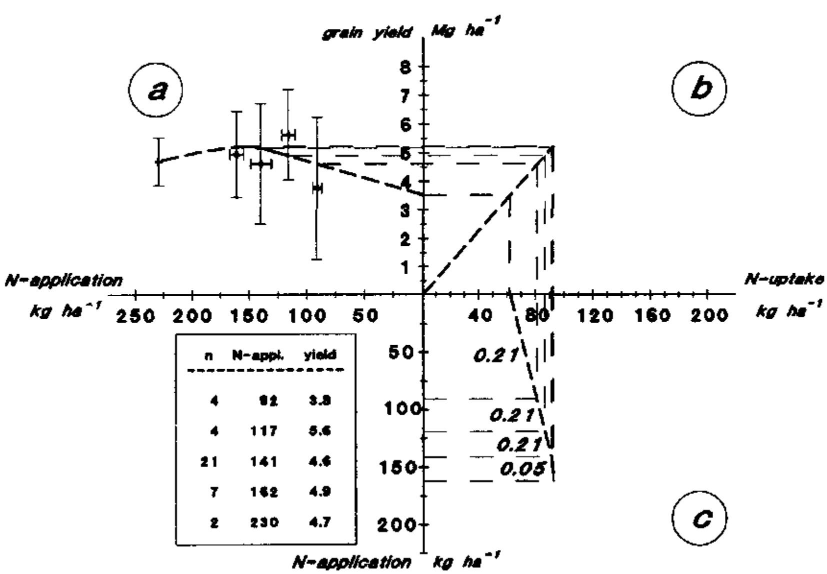

Fig. 2.4 As Fig. 2.3, but this time for soils with SOM between 2 and 3% receiving NBAS.

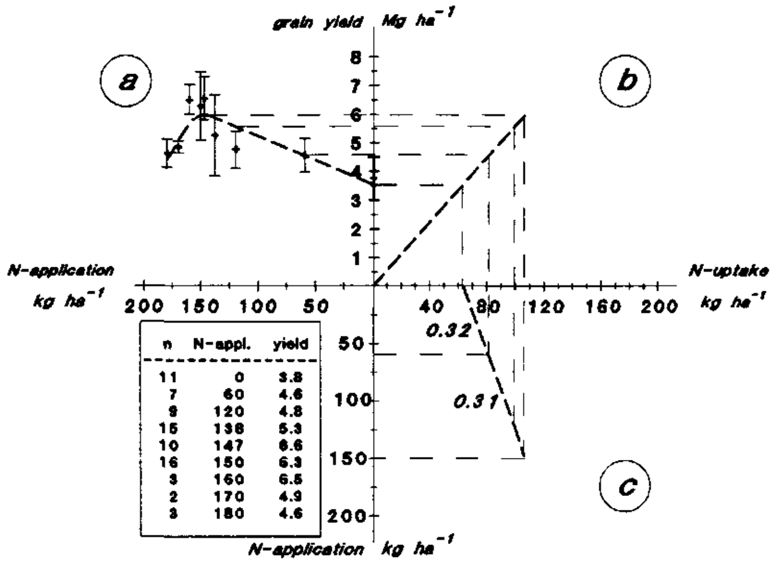

Fig. 2.5 The three quadrant Figure for the Europe survey. Bars indicate standard errors of yield estimates. Numbers aside of the application-uptake curve represent mean apparent nitrogen recoveries calculated for each increment in applied fertilizer-N. Average values of applied N and yields, used to construct quadrant a), are indicated, together with the number of observations used to calculate application and yield averages.

The Camargue survey

The yield-application curve

The data-set for soils under NBAS with more than 3% SOM contained 15 observations at five N application classes. Maximum yields were obtained with N applications between 100 and 125 kg ha^{-1}, after which yields declined strongly (Fig. 2.3a). Up to that level of application, AEFF was 15 to 16 kg kg^{-1}. N timing regimes other than NBAS on these soils did not result in consistent yield-application curves (data not presented).

The data-set for soils containing between 2 and 3% SOM receiving NBAS contained 38 observations in five N application classes (Fig. 2.4). In the yield-application relation only a slight trend could be detected when it was assumed that the yield reaction to the natural N supply was comparable to that observed in the Europe survey. Maximum grain yield was attained at a N application around 150 kg ha^{-1}, resulting in an AEFF of 12 to 13 kg kg^{-1}. No consistent yield-application curves could be established with other timing of N at these soils.

The analysis of data from soils with less than 2% SOM failed to give a satisfying yield-application relation at all.

The lack of any relation between yield and N input when N was split applied or when soils contained less than 2% SOM (regardless application method), suggests that this application method is not always effective in preventing N loss from paddy fields. Even with NBAS, a decrease in SOM resulted in a shift of the N level at which maximum yield was obtained towards higher N applications (Fig. 2.3a and 2.4a). Hence, lower SOM means a lower availability of N for crop production.

The yield-uptake curve

The linear relation between yield and N uptake was derived from EXP89 and EXP90. Maximum yields were obtained at a N uptake near 114 kg ha^{-1} for soils with SOM greater than 3% combined with NBAS (Fig. 2.3b) and around 91 kg N ha^{-1} for soils having between 2 and 3% SOM and receiving NBAS (Fig. 2.4b).

The application-uptake curve

The application-uptake curve for soils with SOM greater than 3% and receiving NBAS showed that an increase of applied N up to around 109 kg ha^{-1} corresponded to an increase in N uptake of 0.25 kg kg^{-1} (Fig. 2.3c).

For the combination SOM 2-3% and NBAS, average ANR was estimated at 0.21 kg kg^{-1} up to a N application of 141 kg ha^{-1} and 0.05 kg kg^{-1} for doses applied between 140 and 160 kg ha^{-1} (Fig. 2.4c).

For the groups receiving NBL or NSPL and for all soils with SOM less than 2%, no consistent relations between N application and yield could be established. Hence, application-uptake curves were not constructed for those soils.

The Europe survey

The yield-application curve

The eye-fitted curve relating average yield and N application in the experiments of the Europe survey showed an increase of yield up to an amount of about 150 kg ha^{-1} of applied N, after which the curve levelled off and subsequently decreased (Fig. 2.5a). The average AEFF till the maximum yield was 15 to 17 kg kg^{-1}. The large variation in grain yield at each N application is due to variations in management and growth conditions between the experiments within the survey.

The yield-uptake curve

The linear relation between yield and N uptake was derived from EXP89 and EXP90 (Fig. 2.5b). Maximum yield, as determined with the yield-application curve, was obtained with a N uptake of about 108 kg N ha^{-1}.

The application-uptake curve

From the application-uptake curve derived from the yield-application and yield-uptake curves, it was estimated that without N fertilization about 62 kg N ha^{-1} was taken up (Fig. 2.5c). This amount is considered as the natural N supply to the crop. Application of 60 kg ha^{-1} increased N uptake by 19 kg, which corresponds to an average ANR of 0.32. About the same ANR fraction (0.31) was found for applied fertilizer N at levels between 60 and 150 kg ha^{-1}.

Discussion

Yield-application and experimentally determined yield-uptake relations permitted to establish average values of ANR for the Europe and the Camargue surveys. The Camargue survey illustrates the complexity of broad field surveys due to variation in environment and management. Sorting of data was therefore carried out on the basis of SOM and N timing, considering existing evidence in literature on the role of these variables in flooded rice soils (Stojanovic and Broadbent, 1956; Patnaik, 1965; Racho and De Datta, 1968).

The assessment of yield-application curves in the Camargue survey appeared only possible when most N was applied basally at soils with reasonably high SOM-levels (2-3% and greater than 3%). Because it was possible to establish relations between yield and N application in the Europe study, it was assumed that soil organic matter was moderate to high at these experimental sites (no farmer fields were included).

The importance of N timing in relation to SOM can be deduced from reported results showing that soils rich in organic matter manifest a large N supplying capacity due to immobilization-remineralization (Patnaik, 1965; Racho and De Datta, 1968). Part of the N mineralized soon after flooding or applied as basal dressing may be temporarily immobilized by the soil microbial biomass and remineralizes later in the growing season (Stojanovic and

Broadbent, 1956; Patnaik, 1965). This remineralized N is, contrary to split applied N, mainly situated in anaerobic soil layers where the risks for losses are relatively small (Craswell and Vlek, 1979; Savant and De Datta, 1982). Hence, more N will be available for crop uptake, resulting in higher grain yields provided N is the main limiting factor. This explains better relationships between yield and N application. The high natural N supply of soils with high SOM (Fig. 2.3) implies that the amount of fertilizer N to be applied for a certain target yield can be reduced compared to that needed on low SOM soils. The risk of over-dosing of N leading to yield reduction is higher on soils high in SOM because N saturation (Stutterheim and Barbier, 1994) or even lodging may already be obtained at moderate N application levels (Fig. 2.3a).

An average value for AEFF between 12 and 17 kg kg^{-1} is obtained in European rice cultivation on soils with SOM greater than 2%. These figures are low compared to reported values of 56 kg kg^{-1} for direct seeded rice in Australia (Humphreys *et al.*, 1987), but in accordance with published data for the Camargue (Barbier and Mouret, 1992). This may indicate that N losses from irrigated rice fields in Europe are substantial. This view is supported by the low values for ANR found in the Camargue survey and with the split applications in EXP89.

The improvement in ANR values obtained with the CRF in EXP89, and especially EXP90, indicate that controlled N release is effective in reducing N loss. Immobilization of fertilizer-N mimics in a certain way a process of slow release, but microbial activity is far from 'controlled', which may cause excessive N uptake. This explains why basal N applications above 100 to 125 kg ha^{-1} at soils in the Camargue survey with more than 3% SOM, decreased average yields, while up to 150 kg N ha^{-1} could be applied without yield reduction within the experiments of the Europe survey and the Camargue farmer soils with SOM 2-3% and NBAS. Hence, one way to improve N efficiency in European rice cultivation is to control N release in the soil. However, this requires additional research to increase the quantitative understanding of N turnover in irrigated soils.

Considerable scope exists for improving N management under European conditions. The AEFF of 32 kg kg^{-1} and the ANR of 0.58 obtained with a CRF application of 100 kg N ha^{-1} in EXP90, compares favourably with the AEFF of 15-17 kg kg^{-1} and the ANR of 0.31-0.32 kg kg^{-1} obtained in the survey of the European experimental fields. The values obtained with the CRF are comparable to those reported for deep point placement of urea in tropical rice (De Datta *et al.*, 1968; Murayama, 1979), still considered one of the most efficient N application methods (Reddy and Patrick Jr., 1976; Craswell *et al.*, 1981; Cao *et al.*, 1984).

Conclusions

- In European rice cultivation the average agronomic efficiency and apparent nitrogen recovery on soils with more than 2% organic matter, range from 12 to 17 kg kg^{-1} and 0.21 to 0.32 kg kg^{-1}, respectively, under condition that fertilizer nitrogen is mainly applied as basal dressing, in quantities adapted to soil organic matter content.
- To prevent yield decline, the amount of N applied as basal dressing on soils with more than 2% soil organic matter must not exceed 110 kg ha^{-1}.
- The relation between N application and yield could not be established for soils with less than 2% soil organic matter because of highly variable yields at different N application levels. Hence, on the basis of this study, basal application of N in European rice cultivation can only be recommended on soils with more than 2% soil organic matter.
- The efficiency of nitrogen in irrigated rice is positively affected by soil organic matter content provided that no over-dosing of N takes place. The risk of yield loss due to excessive N availability is high on these soils.
- In the Camargue survey no consistent yield-application relation could be established when nitrogen was split applied. In the Camargue experiment of 1989 the apparent nitrogen recovery of 0.18 was relatively low. It is concluded that split application of N is not always efficient for yield production.
- Fertilizer N efficiency in irrigated rice systems of Europe can be improved considerably as is demonstrated by the results obtained with controlled release fertilizer.

Chapter 3

Growth and yield formation of irrigated, direct seeded rice as affected by nitrogen.

Abstract To obtain more insight in the growth and yield formation of direct seeded rice, the formation of sink and source capacity for carbohydrates was studied. Additionally, the effects of N management on crop growth and yield formation were analyzed. Data were obtained from two experiments in the South of France in 1989 and 1990. Initial plant density had a large influence on the time course of N uptake rate, apparently *via* its effect on the competition for available soil N. Low shoot N content during the tillering and reproductive growth phases resulted in a decrease of the length of the active tillering period and in low grain numbers per panicle. Leaf appearance rate and tiller appearance rate were not clearly affected by N. During the reproductive phase, the relative mortality rate of stems was linearly related to the decrease in shoot N content. Leaf area was shown to be affected by several growth processes, but simple linear relationships existed between the biomass and area of leaves and cumulative shoot N until flowering. The N use efficiency for leaf production and the specific leaf weight were assessed at, respectively, 19.8 kg kg^{-1} and 418.7 kg ha^{-1}. Although crop N status affected the formation of crop components, N uptake rate *per se* was not a reliable variable to relate to production. Despite this, it was concluded that the risk of a sink limited yield could be minimized by adapted N management. To reduce the risk of a source limited grain production a moderate leaf area with high N content during the post-flowering period was recommended.

Introduction

Yield formation in rice may be considered a process in which available carbohydrates are accumulated in grain during the grain filling period. Yield formation is called sink-limited when carbohydrate production exceeds the rate of accumulation, while the reverse situation represents source-limited production. To obtain insight in the sink and source capacity of a crop, it is necessary to quantify the production of those crop components that determine these capacities. This implies that growth and production needs to be studied at system level, i.e. by considering environment, management and crop characteristics.

Although many studies on rice have been carried out to increase insight in the formation of main stems, tillers, leaves, panicles, spikelets and grains (Murata, 1969; Matsushima, 1979;

Akita, 1989), it remains virtually impossible to adequately calculate rice yield in a given environment. Therefore, in the study presented here, an effort is made to obtain additional information on growth and yield formation of direct seeded rice.

Direct seeded, compared to transplanted rice, is characterised by early canopy closure, a high leaf area production and thus, a high vegetative growth rate. Excessive vegetative growth, however, often leads to tissue nitrogen (N) dilution, and subsequently to carbohydrate shortage and growth reduction in later growth phases (LeMaire and Salette, 1984; Dingkuhn *et al.*, 1990; Schnier *et al.*, 1990a). Hence, interactions between growth and N content of rice are relevant for yield formation and consequently they were taken into account in our study.

In this paper, the production of various crop components that determine post-flowering sink and source capacity for carbohydrates were examined and related to crop N status and time series of shoot growth rate and N uptake rate. Furthermore, the effects of N management on crop growth and yield formation of direct seeded rice were assessed.

Material and methods

Experimental layout and sampling

Two experiments on irrigated direct seeded rice were laid out in a randomized complete block design with four treatments and three replicates in the Camargue region in the South of France (43°18' - 43°24' N), in 1989 (EXP89) and 1990 (EXP90). Experimental plot size was 50 x 12 m. In both years a combined fertilizer at a rate of 34.9 kg P ha^{-1} and 124.5 kg K ha^{-1} was broadcast two days before sowing either with or without a basal N dressing, depending on treatment. A disc harrow was used to incorporate the fertilizer and prepare the seedbed. Seed of the *japonica*-cultivar 'Lido' with an average growth duration of 140 days was broadcast at a rate of 230 kg ha^{-1}. Flooding took place one day after sowing (DAS).

Treatments in 1989 were: a control without fertilizer N application (N0); basal application of 160 kg N ha^{-1} as coated controlled release urea (N1); application of uncoated prilled urea (PU) in two splits of 80 kg N ha^{-1}, at tillering and neck-node differentiation (NND), respectively (N2); and application of uncoated PU in three splits, a basal dressing of 80 kg N ha^{-1} and two splits of 40 kg N ha^{-1} at tillering and NND, respectively (N3). The textural class of the soil was silt loam.

In 1990, a four level single factor design was used with coated controlled release urea at rates of 0 (N0), 50 (N50), 100 (N100) and 150 kg N ha^{-1} (N150), all applied as basal dressing on a loamy sand soil (Stutterheim *et al.*, 1994b).

In EXP89 plants were sampled per block (four treatments per block) at 20, 26, 31, 33, 34, 49, 53, 64, 90, 96, 102, 138, 143 and 144 DAS. In EXP90, complete blocks were sampled at 26, 31, 34, 59, 62, 68, 82, 87, 90, 129, 130 and 132 DAS. In both years, sampling was carried out by harvesting all plants from 0.25 m^2 quadrats. In each experimental plot, four such quadrats were harvested (16 per block) and analyzed for the biomass of shoot, root, stem and leaf, tiller and plant number and shoot N according to Kjeldahl (Method, 1984). Tillers were distinguished from main stems. Leaf area was measured of 10 randomly selected plants per quadrat. The green leaf laminae of each plant were separated from the leaf sheaths and measured with a Delta-T leaf area meter. Leaf area index (LAI), calculated from the four samples per plot, was used for data analysis. At maturity, all leaf material was senescent. In EXP89, leaf appearance on main stems was monitored weekly by marking eight stems per plot and labelling emerged leaves with a small dot of dye. Labelling was postponed until the onset of tillering to avoid possible negative effects of the dye on young plants. Phenological development in both experiments was monitored by registering the onset of tillering, NND and flowering.

Grain dry mass at harvest was determined from each quadrat. Information on panicle morphology was obtained by analysing 20 panicles, randomly selected from each plot. In EXP90, panicles were sampled weekly after flowering to follow the growth of individual grains. Grains were weighed fresh and oven-dry.

Daily weather data were obtained from a nearby weather station.

Data treatment

To analyze treatment effects on shoot growth rate and N uptake rate, logistic curves (Table 3.1) were fitted through plot means of shoot dry mass (M_{sh}) and cumulative shoot N uptake (N_{sh}), both in kg ha^{-1}, using:

$$Y = a_y / (1 + b_y \cdot \exp(-c_y \cdot t)) \qquad (3.1)$$

with:

a_y = curve parameter related to the asymptote of the curve (kg ha^{-1})
b_y = curve parameter related to the symmetry of the curve (-)
c_y = curve parameter related to the steepness of the curve (d^{-1})
Y = shoot dry mass or shoot N content (kg ha^{-1})
t = time after sowing (d)

Table 3.1 Statistics of logistic functions fitted to time series of plot means per treatment (see text). Data were collected in the Camargue experiments of 1989 and 1990.

Experiment 1989, shoot dry mass			
Function: $M = a_M/(1+b_M.\exp(-c_M.DAS))$			
TRT	n	r	Prob > F
N0	15	0.92	0.0001
N1	15	0.98	0.0001
N2	15	0.95	0.0001
N3	15	0.93	0.0001

Experiment 1989, shoot nitrogen content			
Function: $N = a_N/(1+b_N.\exp(-c_N.DAS))$			
TRT	n	r	Prob > F
N0	13	0.83	0.0005
N1	13	0.91	0.0001
N2	13	0.89	0.0001
N3	13	0.87	0.0001

The rates of shoot growth and N uptake were determined as the derivative to time of Equation 3.1 and subsequently plotted (e.g. Fig. 3.1) according:

$$dY/dt = a_y \cdot b_y \cdot c_y \cdot \exp(-c_y \cdot t) / (1 + b_y \cdot \exp(-c_y \cdot t))^2 \qquad (3.2)$$

For statistical analyses, an average sampling date was assigned to three successively sampled blocks, resulting in three replicate means per treatment. Average sampling dates were, 33, 55, 96 and 142 DAS in EXP89, and 30, 63, 86 and 130 in EXP90. To correct for variance heterogeneity, data were transformed to their natural logarithm (Hunt, 1982; Gomez and Gomez, 1984). Subsequently, the standard analysis of variance and the method of Duncan (SAS, 1989) were applied. No curves were fitted to these data.

Table 3.1 (continued)

Experiment 1990, shoot dry mass			
Function: $M = a_M/(1+b_M.exp(-c_M.DAS))$			
TRT	n	r	Prob > F
N0	13	0.92	0.0001
N50	13	0.86	0.0002
N100	13	0.92	0.0001
N150	13	0.91	0.0001

Experiment 1990, shoot nitrogen content			
Function: $N = a_N/(1+b_N.exp(-c_N.DAS))$			
TRT	n	r	Prob > F
N0	13	0.90	0.0001
N50	13	0.84	0.0003
N100	13	0.87	0.0001
N150	13	0.88	0.0001

a_y, b_y, c_y, d_y are function parameters, DAS = days after sowing, TRT = treatment, n = number of replicate means used to fit the function, r = correlation coefficient, Prob > F = level of significance.

The data on yield components per panicle were obtained and analyzed differently for both experiments. In EXP89, the number and locations of differentiated and degenerated branches and spikelets per panicle were estimated on the 20 panicles collected per plot. Primary branches per panicle were numbered in acropetal direction starting from the neck-node. Because abortion of branches and spikelets was restricted to the lower part of the panicle, only the basal five differentiated primary branches with their secondary branches and spikelets were analyzed. Abortion of primary branches, secondary branches or spikelets was recorded by counting the vestiges of these organs on the panicle at harvest (Matsushima, 1979).

In EXP90, plot averages of individual grain dry mass (M_g) and total grain number per panicle were calculated weekly from the 20 panicles per plot. Growth curves of individual grains were derived by fitting logistic functions to the data per plot (c.f. Eqn. 3.1). The mean curve per treatment was calculated by averaging the curve-parameters. Statistical analysis of the parameters was performed by an analysis of variance. Subsequently, individual grain growth rate in each treatment was calculated by using the derivative of each average logistic function (c.f. Eqn. 3.2). By definition, maximum growth rate is attained at the point of inflection (t_i), calculated as $\ln(b_g)/c_g$. A maximum 10-day mean growth rate (M_g') was calculated as the mean of the growth rate at t_i - 5 and t_i + 5 days.

Results

Rates of growth and N uptake

In EXP89, growth rate through time was lowest at N0 (Fig. 3.1), corresponding to relatively low N uptake rates (Fig. 3.2). At the other treatments both rates were not distinctively related. Initial average plant densities in that experiment were 338, 377, 389 and 427 m^{-2} at N0, N1, N2 and N3, respectively. Maximum individual plant N uptake rate per treatment was calculated by dividing maximum shoot uptake rate by plant density. This resulted in: $6.87x10^{-3}$, $9.19x10^{-3}$, $9.67x10^{-3}$ and $9.29x10^{-3}$ g $plant^{-1}$ d^{-1} for N0, N1, N2 and N3, respectively.

In EXP90, growth and N uptake rates at N0 were relatively low. From the curves at the other treatments again no conclusions could be drawn on a possible relationship between both rates (Fig. 3.1 and 3.2). Average plant density per treatment was 702, 687, 646 and 664 m^{-2} for N0, N50, N100 and N150, respectively. N uptake rate through time in EXP90 (Fig. 3.2) was relatively low from the onset of tillering (25 DAS) till the later part of the reproductive phase (50-84 DAS). Some N uptake took place during the late reproductive and grain filling phases (84-131 DAS), probably caused by a high crop N demand (Nielsen, 1983; De Willigen and van Noordwijk, 1987). Maximum individual plant N uptake rates were estimated at $1.21x10^{-3}$, $2.18x10^{-3}$, $2.29x10^{-3}$ and $3.11x10^{-3}$ g $plant^{-1}$ d^{-1} for N0, N50, N100 and N150, respectively.

Hence, large differences in plant density between both experiments existed. The low densities in EXP89 corresponded to relatively high maximum plant N uptake rates, while the reverse held in EXP90.

Shoot N percentage (NP_{sh}) was calculated using the ratio of cumulative shoot N content to shoot dry mass (N_{sh} / M_{sh}). In all treatments of EXP89 the N concentration of the crop increased till about mid-tillering, while in EXP90 it monotonously decreased (Fig. 3.3). During the grain filling phase, NP_{sh} in both experiments was comparable. This is confirmed by measured shoot N contents at flowering: in EXP89 1.2% ± 0.1% averaged over all treatments, and in EXP90 0.9% ± 0.1%.

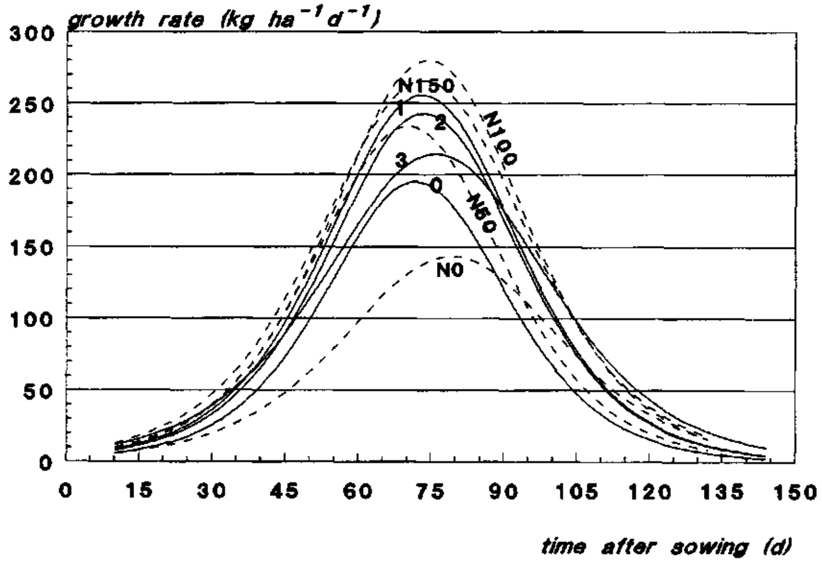

Fig. 3.1 Calculated shoot growth rate through time for treatments in the 1989 (solid lines) and 1990 (broken lines) experiments. 0, 1, 2 and 3 are treatments N0, N1, N2 and N3 in '89, respectively (see text).

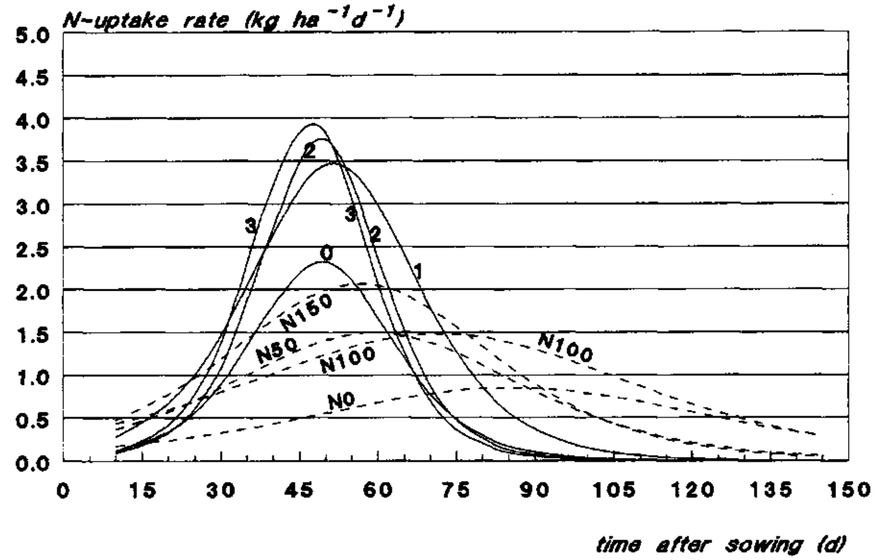

Fig. 3.2 Calculated shoot nitrogen uptake rate through time in the 1989 (solid lines) and 1990 (broken lines) experiments. Symbols as in Fig. 3.1.

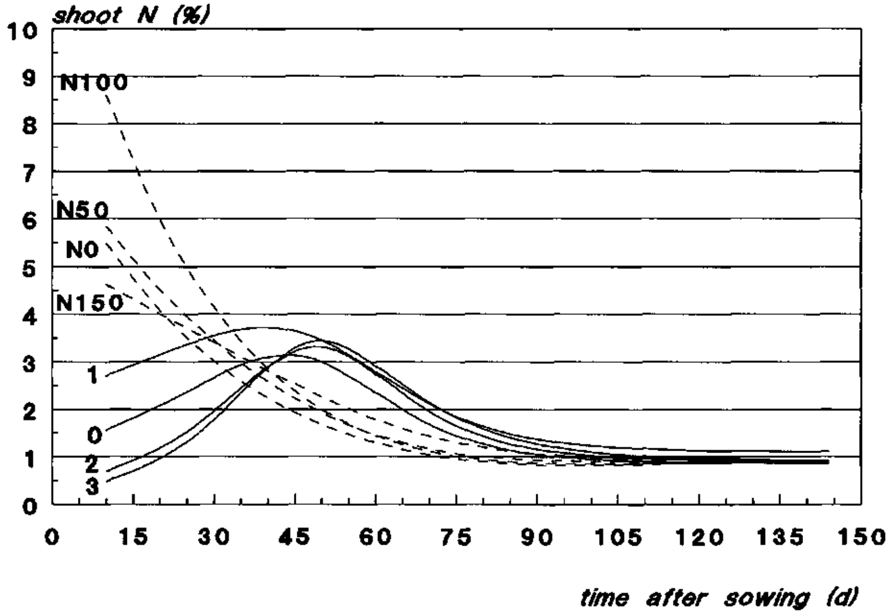

Fig. 3.3 Calculated shoot nitrogen content through time in the experiments of 1989 (solid lines) and 1990 (broken lines). Symbols as in Fig. 3.1.

Leaf appearance, tillering and tiller mortality

In EXP89, maximum tillering was observed at 56 DAS, with the lowest and highest average number of tillers per plant at 2.6 in N0, and 3.2 in N1. Leaf appearance rate did not vary significantly among treatments in EXP89 (Fig. 3.4). This suggests that also tiller formation rate was independent of N treatment, considering existing evidence that appearance of leaves and tillers proceeds at similar rates (Masle-Meynard, 1980; Yoshida, 1981; Hanada, 1982; Durr, 1984).

In EXP90, maximum tillering was observed at 30 DAS and the lowest and highest average number of tillers per plant was 1.1 at N0 and 1.4 at N150.

Hence, in both experiments, maximum tiller number per plant did not vary to a large extent among treatments. Between the two experimental years, however, differences were important. The period of active tillering was much longer in EXP89 than in EXP90.

In both years a considerable loss in the number of stems was observed, especially during the reproductive phase. By expressing the number of stems at each moment relative to that at NND stage, the relative stem mortality (RSTM) was obtained. RSTM was linearly related

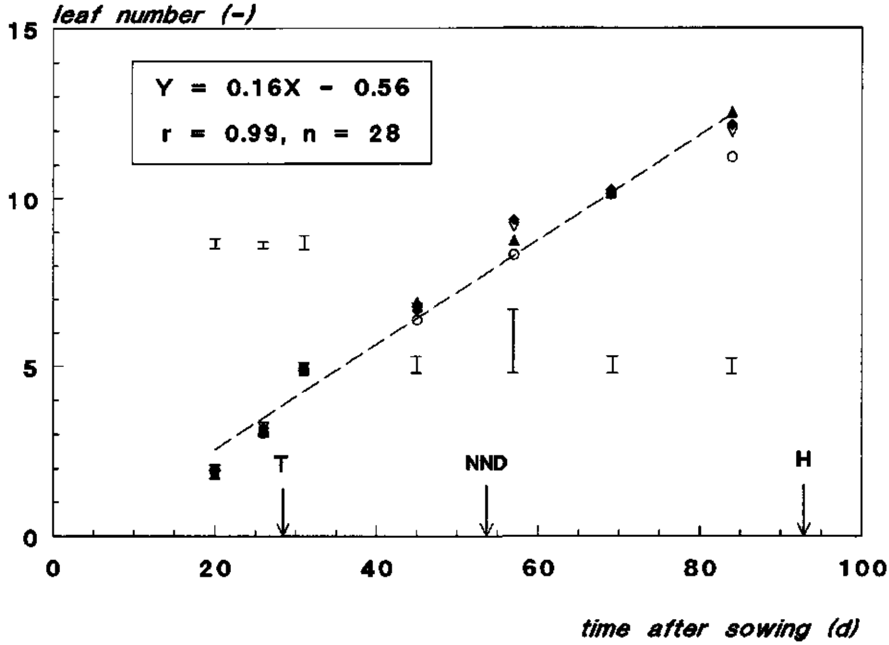

Fig. 3.4 Leaf number at main stems against time in the experiment of 1989. Leaves were numbered in order of appearance. Bars indicate the least significant difference at the 5% level (Duncan) between treatment means. ○ = N0, ♦ = N1, ▽ = N2 and ▲ = N3 (see text).

to the decline in shoot N content (ΔNP_{sh}) during the reproductive phase:

$$RSTM = 0.32 \cdot NP_{sh} - 0.05 \; (r = 0.89 \; [0.01\%]; \; n = 24) \qquad (3.3)$$

Leaf area expansion and phenological development

Between treatments in EXP89, significant differences in maximum leaf size existed between leaves at identical positions on the main stem. At N0, leaves were smaller at the 10th and 11th position, while in N1 leaves were larger at the 9th position. At other positions, differences were not significant (data not presented). Total leaf number per main stem was lowest at N0 (Fig. 3.4).

The dates of the onset of tillering, NND and flowering were comparable among treatments in each experiment (data not presented). This indicates absence of a significant N effect on phenological development rate. This may also be concluded from the leaf appearance rate in EXP89 (Fig. 3.4), considering that in rice and wheat leaf appearance rate is related to phenological development rate (e.g. Matsushima, 1979; Kirby, 1990; Miglietta, 1992).

Up to flowering, the following relations between pooled plot means of leaf dry mass (M_l in kg ha^{-1}), N_{sh} and LAI over both experimental years existed:

$$M_l = 19.8 \cdot N_{sh} - 9.1 \; (r = 0.94 \; [0.01\%]; \; n = 72) \quad (3.4)$$

$$M_l = 418.7 \cdot LAI - 46.8 \; (r = 0.98 \; [0.01\%]; \; n = 63) \quad (3.5)$$

$$LAI = 0.05 \cdot N_{sh} - 0.1 \; (r = 0.95 \; [0.01\%]; \; n = 72) \quad (3.6)$$

Hence, N-use efficiency for leaf production, and specific leaf weight, was about constant until flowering (respectively 19.8 kg leaf dry mass per kg N absorbed and 418.7 kg leaf dry mass per ha leaf). A comparable linear relation between LAI and N_{sh} has been previously found for wheat (Groot, 1987).

Leaf dynamics are thus strongly related to cumulative shoot N, while no apparent relationship existed between the rates of growth and N uptake. Maximum growth rate at each treatment, plotted against the total shoot N content at the moment of maximum growth (Fig. 3.5), demonstrates that the N-use efficiency for growth rate (kg dry mass ha^{-1} d^{-1} per kg N)

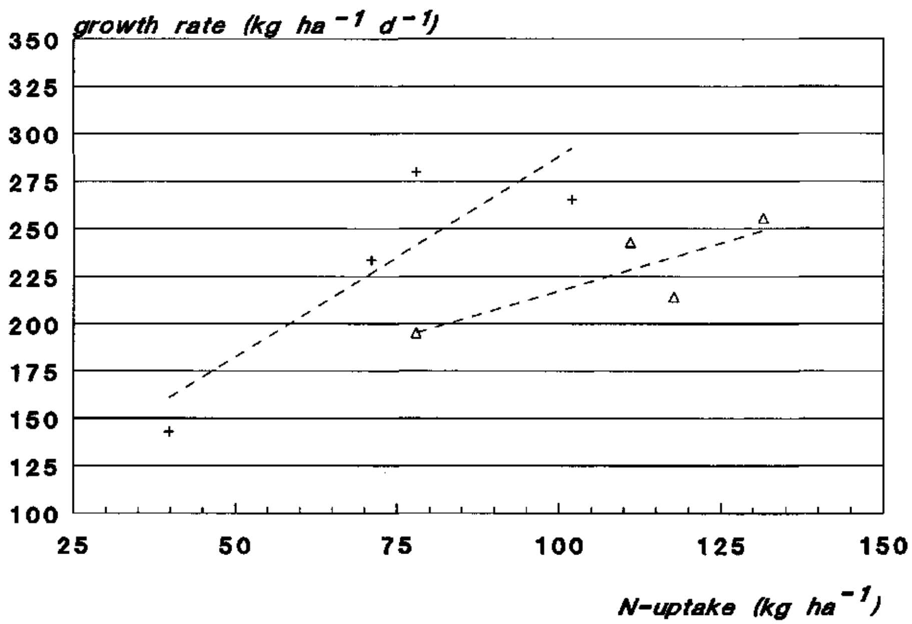

Fig. 3.5 Maximum growth rate per treatment against cumulative shoot nitrogen uptake at maximum growth. + = treatment means experiment 1990, ▵ = treatment means experiment 1989.

was higher in EXP90 than in EXP89, at least at the moment of maximum growth. This implies that in both years comparable growth rates could have been realized at different levels of cumulative shoot N.

Yield formation and yield components

Yield at N0 EXP89 was limited by low panicle density, despite some compensation through higher grain weights (Table 3.2). Final grain yields at N1, N2 and N3 were not significantly different, which indicates that total carbohydrate supply to grains must have been comparable under these three treatments, despite differences in LAI-values at flowering (Table 3.2).

Grain numbers at N0 and N2 were mainly reduced because less primary branches were differentiated (Table 3.3). The relatively limited abortion of secondary branches and the better grain filling in N0 compensated somewhat for the lower grain number. In N2, significantly more secondary branches were aborted than in the other treatments.

Contrary to EXP89, grain number per panicle mainly limited grain yields in EXP90 (Table 3.2). These numbers increased with higher N application levels. The high growth rate during the reproductive phase at N100 seems at first side contradictory with reduced grain numbers,

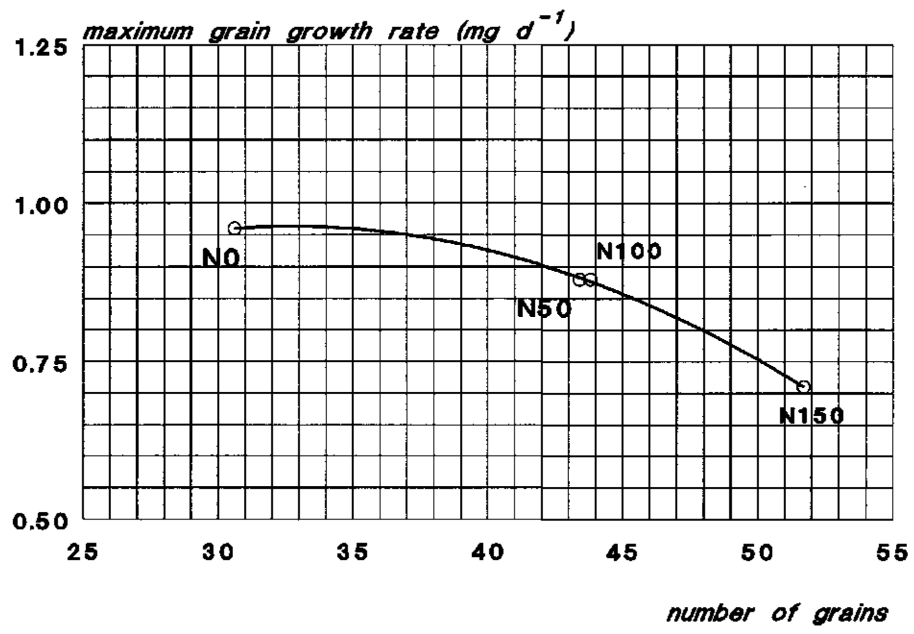

Fig. 3.6 Maximum growth rate of individual grains as function of the number of filled grains per panicle in the experiment of 1990. Symbols represent treatment means.

Table 3.2. Yield components and production obtained in the Camargue experiments of 1989 and 1990. Treatment averages of each variable that are followed by the same letter are not significantly different at the 5% level. LAI = leaf area index.

Experiment 1989	N0	N1	N2	N3
Panicles per m^2	542[a]	709[b]	684[b]	678[b]
Tot. no. of grains per panicle	69.1[ab]	72.0[b]	63.9[a]	70.2[b]
- completely filled	62.4[a]	58.9[a]	56.3[a]	61.2[a]
- partly filled or empty	6.7[a]	13.0[b]	7.6[a]	9.0[a]
Individual grain dry matter (mg)	21.9[a]	20.3[c]	21.2[b]	20.8[bc]
Final grain dry mass (g m^{-2})	530.8[a]	649.5[b]	648.6[b]	654.5[b]
LAI at flowering	3.98[a]	6.97[c]	5.36[bc]	5.19[ab]

N0 = no N-application, N1 = 160 kg urea-N basally applied as controlled release fertilizer, N2 = two split applications of 80 kg urea-N each as prilled urea, N3 = three split application in fractions of 80, 40 and 40 kg urea-N as prilled urea.

Experiment 1990	N0	N50	N100	N150
Panicles per m^2	620[a]	615[a]	676[a]	691[a]
Tot. no. of grains per panicle	32.4[a]	46.2[b]	47.8[b]	57.5[b]
- completely filled	30.6[a]	43.4[b]	43.8[b]	51.7[b]
- partly filled or empty	1.8[a]	2.8[a]	4.0a[b]	5.8[b]
Individual grain dry matter (mg)	24.7[a]	24.5[ab]	23.9[b]	24.5[ab]
Final grain dry mass (g m^{-2})	411.3[a]	580.4[b]	728.5[c]	732.7[c]
LAI at flowering	1.74[a]	3.27[b]	4.71[c]	5.34[c]

N50, N100 and N150 indicate the basal application of, respectively, 50, 100 and 150 kg urea-N as controlled release fertilizer.

but when growth rate is expressed on a plant basis, a reduced number of spikelets per panicle is consistent with a carbohydrate shortage on the individual plant level (c.f. Matsushima, 1979).

Individual grain growth was less affected by N management (Table 3.4). Parameters a_g, b_g and c_g (c.f. Eqn. 3.1) were not significantly different among N application levels. M_g' was

Table 3.3 Panicle morphology at different nitrogen treatments in the 1989 Camargue experiment. Numbering of branches started at the base of a panicle. Different letters between values in a row indicate a significant difference at the 5% level.

Experiment 1989	N0	N1	N2	N3	CV (%)
no. of differentiated PB	7.9[a]	8.5[b]	8[a]	8.5[b]	8.3
no. of spikelets on first 5 PB	39.8[a]	36.4[bc]	35.8[c]	37.8[b]	14.3
% aborted of PB 1	5.12[a]	6.13[ab]	7.40[b]	5.90[a]	33.6
% aborted of PB 2	1.39[a]	1.59[a]	2.13[a]	1.65[a]	92.3
% aborted of PB 3	0.06[a]	0.00[a]	0.10[a]	0.11[a]	254.6
% aborted SB	14.34[a]	18.77[b]	18.89[b]	18.09[b]	20.9

N0 = no N application, N1 = 160 kg urea N basally applied as controlled release fertilizer, N2 = two split applications 80 kg urea N each as prilled urea, N3 = three split application in fractions of 80, 40 and 40 kg urea N as prilled urea. PB = primary rachis branches of a panicle, SB = secondary rachis branches. CV = Coefficient of variation.

lowest at N150. Although differences in M_g' were not significant, a tendency existed for this maximum growth rate to decrease with increasing grain number per panicle (Fig. 3.6). Only t_i was significantly different among treatments. At N150, t_i was 3.6 to 4.6 days longer than at other treatments (Table 3.4). As a consequence, physiological maturity was delayed in N150.

Hence, in EXP90 yield was mainly sink limited, except at N150. In EXP89, the relatively high leaf area at flowering did not contribute to higher yields, which wrongly could be interpreted as a sink limited yield. The relatively high number of grains and panicles per unit surface (Table 3.2) indicate that other factors than leaf area limited the source capacity of the crop.

Overall, the highest yields per unit surface were obtained at N100 and N150 in EXP90. This corresponded to the high growth rates in these treatments during the panicle formation stage (Fig. 3.1) resulting in higher grain numbers per panicle. Lower temperatures during the grain filling period in EXP90 may also have played a decisive role in creating yield differences between both years (Spiertz, 1977; Vos, 1981). Cumulative average 24 h temperature during the first 20 days after flowering was 497.5 ^{0}C in EXP89 and 459.8 ^{0}C in EXP90.

Table 3.4 a) Treatment averages of individual grain dry mass (mg) through time as obtained in the 1990 Camargue experiment. b) Characteristics of average logistic curves obtained for each N-application level in that experiment. Grain dry mass data per treatment and curve parameters per N application level, are not significantly different at the 5% level if they have identical letters.

a)

TIME AFTER HEADING (d)	N0	N50	N100	N150
2	3.6[a]	3.5[a]	3.4[b]	3.3[b]
9	4.3[ab]	5.4[a]	3.4[b]	3.7[b]
16	9.2[a]	9.0[a]	8.6[a]	7.2[a]
23	17.2[a]	17.3[a]	15.5[a]	11.0[b]
27	20.5[a]	19.8[a]	18.2[ab]	15.3[b]
38	23.5[a]	22.7[ab]	22.1[ab]	21.2[b]
48	23.2[a]	22.7[a]	22.3[ab]	21.2[b]

N0, N50, N100 and N150 indicate the basal application of, respectively 0, 50, 100 and 150 kg urea N as controlled release fertilizer.

b)

N-APPLICATION (kg ha^{-1})	b_g (-)	c_g (d^{-1})	a_g (mg)	t_i (d)	M_g' (mg d^{-1})
0	20.3[a]	0.167[a]	24.0[a]	17.8[a]	0.96[a]
50	16.7[a]	0.160[a]	23.5[a]	17.3[a]	0.88[a]
100	21.1[a]	0.163[a]	22.9[a]	18.8[a]	0.88[a]
150	17.8[a]	0.127[a]	23.4[a]	22.4[b]	0.71[a]
C.V. (%)	38.7	18.1	2.7	5.6	13.9

b_g = curve parameter related to the symmetry of the growth curve. c_g = curve parameter related to the steepness of the growth curve. a_g = curve parameter related to the saturation asymptote of the growth curve. t_i = day after heading at which the point of inflection of growth curve is reached. M_g' = average maximum growth rate of individual grains. C.V. = coefficient of variation of parameter estimates.

Discussion

The formation of yield determining crop components in direct seeded rice is greatly affected by N. However, the existence of feed-back between N-dependent processes makes quantification of N effects difficult, e.g. tiller production can be stimulated by N application, while at a later growth stage high tiller density may result in N shortage. Hence, a direct quantitative advice in terms of N management can not be given on the basis of this study, but enough evidence was obtained to discuss the issue of N management in relation to increased post-flowering sink and source capacity in qualitative terms.

Initial plant density had a large influence on the dynamics of shoot N uptake rates. It was shown that on a soil low in fertility (EXP90), high plant densities lead to early competition for soil N as indicated by the low maximum plant uptake rates and the early shoot N dilution.

A simple equation previously defined by Nielsen (1983) can be used to illustrate these findings:

$$dN_c / dt = D \cdot I_N \cdot L \qquad (3.7)$$

where:

dN_c/dt = N uptake rate of the crop (kg ha^{-1} d^{-1})
D = Plant density (ha^{-1})
I_N = Net inflow rate of N into roots (kg m^{-1} d^{-1})
L = Effective root length per plant (m)

Hence, N uptake rate can increase with D, I_N or L. However, these parameters are not independent. Average individual plant N uptake rate ($I_N \cdot L$) depends on plant properties and on soil N availability. In the exponential growth phase, plants growing at moderate densities (thus without severe competition for N), will increase their N uptake rate ($I_N \cdot L$). As a result, total shoot N uptake also increases. However, if D is too high and/or soil N availability is relatively low, early competition for N may negatively affect $I_N \cdot L$ resulting in lower shoot N uptake rates.

An early decrease in individual plant N uptake rate, and thus in tissue N concentration, negatively affects tillering activity of such a plant (Durr, 1984; Wada *et al.*, 1986). Practically, this means that at a given level of soil fertility, plant populations at high density will produce fewer tillers than low density populations. Application of fertilizer N may then help to increase the number of tillers by extension of the active tillering period.

During the reproductive growth phase, shoot N percentage decreased in both experimental years and relative stem mortality was linearly related to that decrease. Also, low grain numbers per panicle existed in most of the treatments in EXP90 due to a combination of high density and low shoot N status.

Stem mortality and reduced spikelet production, both, point to a shortage in carbohydrate availability on the individual plant level during the reproductive growth phase. As it has been shown that the N content of leaves and their photosynthetic capacity are closely related (c.f. Kisthitani *et al.*, 1972; Shieh and Liao, 1987; Sinclair and Horie, 1989), the low carbohydrate production during the reproductive growth phase may be attributed to the low shoot N status.

The high growth rates that were realized in EXP90 due to high plant densities, and the high N-use efficiency for growth rate, resulted in high yields in N100 and N150. Also an effect of low temperatures which could have favoured grain filling was not excluded. The relatively high N-use efficiency for growth rate may be related to the late N uptake in EXP90, which could have led to N enrichment of active leaf material.

Fertilizer N application in the first half of the reproductive growth phase may thus serve for maintaining main stems and tillers and for increasing the spikelet production.

In our experiments leaf area was affected in several ways: 1) the lamina area of individual leaves decreased when no N was applied (c.f. Biscoe and Willington, 1985), 2) the duration of tiller formation varied, presumably in dependence of shoot N content (c.f. Ishizuka and Tanaka, 1969; Schnier *et al.*, 1990b), 3) the relative loss rate of stems varied in dependence of shoot N dynamics (c.f. Dingkuhn *et al.*, 1990), and 4) the total number of leaves that emerged on the main axis was lower when no N was applied (c.f. Durr, 1984). Despite these different mechanisms, we arrived at a linear relation between leaf biomass, or leaf area, and cumulative N uptake until flowering. Using N uptake as input, these relations permit calculation of the increase in LAI on a daily basis, which can be used for estimation of daily crop production. This, however, was beyond the scope of this paper.

Grain yield will mainly be determined by weather and source capacity during the grain filling phase, provided the grain sink capacity is assured by N application at the reproductive growth phase and pest and diseases are well controlled. However, it was shown that only a high leaf area around flowering is not a guarantee for sufficient source capacity. Moreover, a high leaf area may be counter-productive when respiration increases through high temperatures. Hence, to reduce the risk of source limitation through weather, a moderate leaf area seems advisable. An other aspect that affects source capacity is the remobilization of amino-acids and ageing of leaves (e.g Sinclair and de Wit, 1975). These processes decrease the photosynthetic capacity. Additional N supply at the onset of grain filling may partly reduce these self-destructing processes. In accordance with other findings (c.f. Evans and Wardlaw, 1976; Yoshida and Parao, 1976), we advise to maintain a moderate leaf area with high N content at the onset of the grain filling phase to reduce the risk of source-limited grain production.

The lack of relationship between the rates of growth and N uptake may be explained by a different impact of environment on both rates, e.g. an increase in temperature may decrease growth rate through higher respiration, but it may increase N uptake rate through higher root or mineralization activity. Furthermore, the reaction time of N uptake rate to limiting conditions is relatively short compared to that of growth rate. Hence, N uptake rate *per se* is not a reliable variable to relate to crop production.

The results stress the importance to take the state of crop and soil into account when formulating fertilizer recommendations. In the Camargue region, these factors are only taken into account on an intuitive basis when applying fertilizer N, as to our knowledge is not exceptional in rice cultivation.

Chapter 4

Simulation of nitrogen limited growth of irrigated rice with a simple crop growth model

Abstract To simulate N limited production of irrigated rice, a simple mechanistic model was developed, called NGROW-RICE. As basis for the model three mechanistic equations were used, expressing, respectively, interception of daily global radiation by the crop as function of total leaf nitrogen (N) per unit ground area, crop CO_2-exchange as function of intercepted radiation, and daily crop growth rate derived from CO_2-exchange rate. The effect of diffuse radiation on energy conversion efficiency (g CO_2 MJ^{-1}) was explicitly accounted for in the model, but environmental effects other than radiation and crop specific characteristics were implicitly expressed in a site specific scaling factor. Data from six experiments on N management in irrigated rice, carried out in China and the Philippines, suggested a linear relationship between energy conversion efficiency and the fraction diffuse light in the incident radiation. Simulation of crop growth in those experiments and four additional experiments in India and France, resulted in good agreement between simulated and observed crop production at various N treatments. NGROW-RICE can be used as a tool to evaluate crop growth under N limiting conditions. Combined with a routine that mimics N uptake of a crop, it may be used in optimizing N management practices in rice.

Introduction

The transformation of light energy into chemical energy by photosynthesis is the primary driving force behind crop growth. De Wit (1965) and Monteith (1972) expressed the efficiency with which crops or natural communities produce dry matter (DM) as the product of seven factors: 1) the position of the earth with respect to the sun, 2) the transmissivity of the earth's atmosphere, 3) the spectral composition of solar radiation and the optical properties of the foliage, 4) the number of light quanta per unit CO_2 reduced, 5) the fraction of radiation intercepted by a canopy, 6) the finite rate at which CO_2 molecules can diffuse from the atmosphere to the chloroplasts, and 7) the fraction of assimilate not used for respiration.

In explanatory crop growth models some or all of these factors are comprehensively treated (De Wit, 1965; De Wit *et al.*, 1978; Goudriaan, 1982; Ritchie and Otter, 1985). The development and application of such models provide insight in the relations among fundamental processes operating at different hierarchical levels, and contribute to the understanding of agricultural production systems. However, complex explanatory models are less suitable for use in applied research and extension work because their primary objective is conceptualization and/or explanation. For the purpose of management and instruction, condensed summary models are better suited (Rabbinge and De Wit, 1989).

In irrigated rice, limited crop production due to high N losses (Craswell and Vlek, 1979; Vlek and Byrnes, 1986) resulting in low N recoveries (Patrick and Reddy, 1976; Stutterheim *et al.*, 1994b) are commonly observed. Hence, to determine optimum nitrogen (N) fertilizer strategy in terms of total dry matter production or N loss in irrigated rice, a simple model called ORYZA_0 was developed (Ten Berge *et al.*, 1994). In ORYZA_0, N uptake and the utilization of crop N for dry mass production are calculated as function of crop N status and N management. However, light interception and its conversion into dry matter cannot be separated in this model, which makes insight and understanding difficult. Therefore, a new module on N limited growth of irrigated rice, called NGROW-RICE, was developed in which these processes are separated.

In this paper, the principles of NGROW-RICE, and the results of calibration and testing on field data from China, India, the Philippines, and France are presented.

Material and methods

Model description

A limited number of relations are incorporated in NGROW-RICE: (i) interception of daily global radiation as function of total leaf N per unit soil surface (Eqn. 4.1); (ii) energy conversion efficiency as function of the fraction diffuse in the incident radiation (Eqn. 4.2); (iii) daily CO_2-exchange rate of the crop as function of daily intercepted radiation and the energy conversion efficiency (Eqn. 4.3), and; iv) daily crop growth rate as function of the crop CO_2-exchange rate (Eqn. 4.4), i.e.

$$R_i = R_g \cdot (1 - EXP(-k \cdot N_l) \qquad (4.1)$$

$$\alpha = c_1 + c_2 \cdot F(R_g) \qquad (4.2)$$

$$CER = \alpha \cdot R_i \cdot 10^{-6} \qquad (4.3)$$

$$CGR = c_s \cdot 10 \cdot 0.75^2 \cdot 30/44 \cdot CER \quad (4.4)$$

with:

α	= Energy conversion efficiency (g CO_2 MJ^{-1})
c_1	= Intercept of the curve relating α and $F(R_g)$ (g CO_2 MJ^{-1})
c_2	= Slope of the curve relating α and $F(R_g)$ (g CO_2 MJ^{-1})
CER	= Crop assimilation rate (g CO_2 m^{-2} d^{-1})
CGR	= Crop growth rate (kg DM ha^{-1} d^{-1})
c_s	= Scaling factor dependent on experimental conditions (-)
$F(R_g)$	= Fraction diffuse in the incident radiation (-)
k	= Light extinction factor dependent on total leaf N (ha kg^{-1})
N_l	= Total leaf N per unit soil surface (kg ha^{-1})
R_g	= Incident global radiation (J m^{-2} d^{-1})
R_i	= Intercepted radiation (J m^{-2} d^{-1})
R_g	= Incident global radiation (J m^{-2} d^{-1})

Equation 4.1 was derived from the widely used relationship between incoming and intercepted radiation (e.g. De Wit, 1965; Goudriaan, 1977) as expressed by:

$$R_i = R_g \cdot (1 - EXP(-0.7 \cdot LAI)) \quad (4.5)$$

By plotting observed values of pre-flowering LAI against values of total leaf N as measured in one of the considered experiments (Ph93D, Table 4.1), LAI was expressed as linear function of N_l. The slope of this curve multiplied with 0.7 from Equation 4.5 resulted in a value of k as used in Equation 4.1. Hence, in the model the light extinction factor is explicitly related to leaf N per unit soil surface instead of leaf area index (LAI).

Assimilation rate CER is derived from intercepted radiation and an energy conversion efficiency α (Eqn. 4.2), i.e. the efficiency with which Ri is used in the photosynthetic process (Evans and Farquhar, 1991; Goudriaan, 1982). The efficiency of carbon assimilation increases with the fraction diffuse radiation ($F(R_g)$), because diffuse light is more uniformly and efficiently distributed over a canopy of leaves that may become light saturated at high intensities.

CGR is derived from CER using a relationship (Eqn. 4.4) comparable to that of Sinclair and Horie (1989). The Equation describes hexose production per unit assimilated CO_2 (30/44), accounts for the cost of maintenance respiration, set at 25% of CER, and uses the biochemical conversion coefficient describing the production of crop biomass from hexose (0.75). The parameter value representing the biochemical conversion efficiency may vary with crop status and variety. This also holds for maintenance, which in addition is strongly influenced by temperature. To account for these variations and for variations in α, the scaling factor c_s was introduced whose value is derived by calibration per experiment. Total cumulative dry mass production over the growing season results from integration of daily growth rates.

To obtain grain yields, final calculated biomass is multiplied with a predefined harvest index (HI). HI depends on varietal characteristics (Singh and Stoskopf, 1971; Akita, 1989; Dingkuhn *et al.*, 1991), so information on that varietal trait is necessary to simulate yield adequately. Because this information was only partly available, yields were not assessed in this study.

The time step of calculation in the model is one day. Apart from latitude and incoming global radiation, dates of sowing cq. transplanting, flowering and harvest, and data on cumulative leaf N, are required as input.

Data from six experiments, carried out in China and the Philippines, were used to establish the relationship between $F(R_g)$ and α (Eqn. 4.2). Using Equation 4.4, values for $c_s \cdot CER$ were derived from observed growth between the sampling dates of the experiments. By dividing these average CO_2-exchange rates by average R_i during the relevant sampling intervals, 214 values of α were obtained. Subsequently, the relationship expressed by Equation 4.2 was established by plotting α against average values of the fraction diffuse in the radiation received during the respective time intervals. The best fit, expressed by the values of c_1 and c_2 was used for all further simulation work. Post-flowering growth was not considered for establishment of α because mortality could have been important at that stage. $F(R_g)$ was calculated with the subroutine SUASTC (Penning de Vries *et al.*, 1989) using Julian daynumber, latitude and measured daily total global radiation as input.

Model calibration

Calibration was carried out to determine an appropriate value for c_s per experiment. This was done by randomly choosing one of the N treatments in the experiment, and fitting simulated crop production to the observations. A best fit was obtained by varying the value of c_s. The optimum value for c_s was subsequently used to simulate crop production in the remaining treatments of that experiment.

The differences between observations and simulations per treatment were averaged to express the absolute simulation-observation difference (SOD) per treatment. An average SOD per experiment was calculated (SOD_e) to provide a measure for model performance. Additionally, predicted means of crop dry mass were plotted against observed ones.

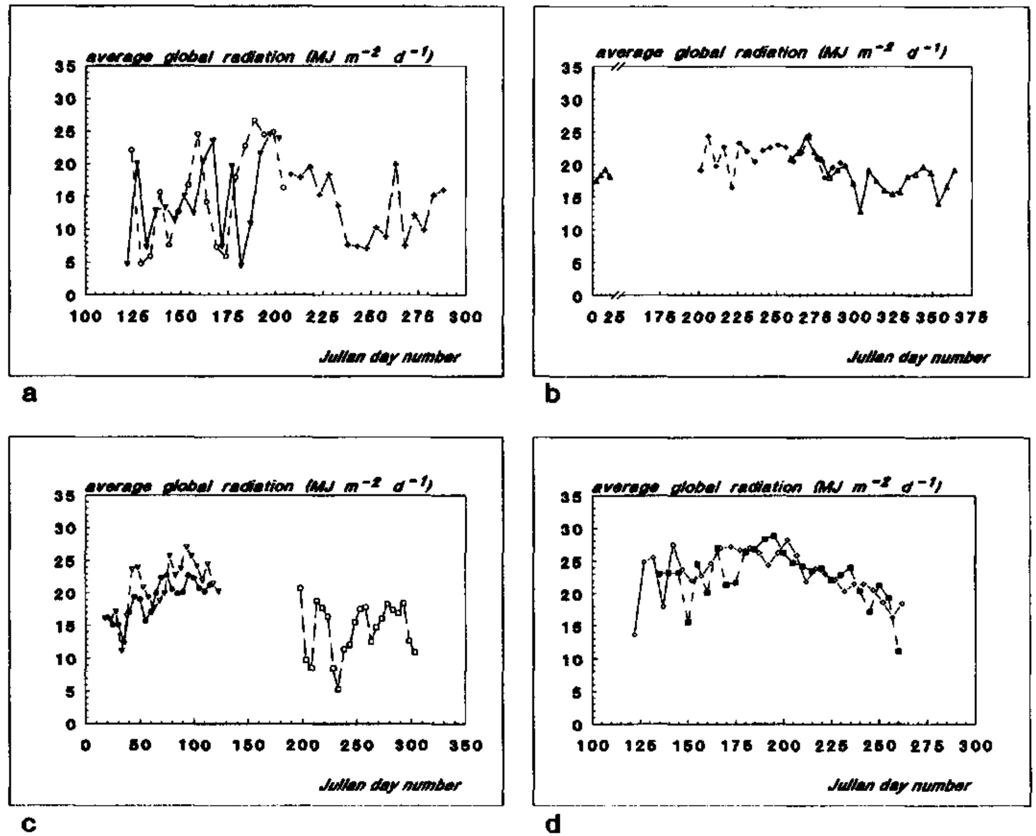

Fig. 4.1 Time series of five day averages of incident global radiation for: a) China, Jiangxi; ○ = 1988 early season, + = 1988 late season, ▾ = 1989 early season. b) India, Thanjavur; △ = 1991-'92 wet season, ◆ = 1992 dry season. c) Philippines, Los Banos; □ = 1991 wet season, • = 1992 dry season, ▿ = 1993 dry season. d) France, Camargue; ◊ = 1989, ■ = 1990.

For eight experiments from the network of Simulation and System Analysis for Rice Production (Ten Berge *et al.*, 1994), and for two experiments from the Laboratory of Agrarian System Research (LECSA) of the National Institute of Agronomic Research (INRA) in France (Stutterheim and Barbier, 1994; Stutterheim *et al.*, 1994b), values for the scaling factor were assessed.

Three experiments were performed in 1988 and 1989 (Ch88a, Ch88b and Ch89) in Jiangxi province in China (28° 36' N) by the Agricultural University of Jiangxi. Treatments involved rate and timing of fertilizer N to hybrid rice.

Three experiments were done at IRRI, Los Banos in the Philippines (14° 06' N), one in the 1991 wet-season (Ph91W), and two in the dry season of 1992 (Ph92D) and 1993 (Ph93D), respectively. In 1991, treatments consisted of application of various amounts of N in several split dressings, using different varieties (Table 4.1). In 1992, different N application levels, but the same varieties were used (Kropff *et al.*, 1993). In the experiment of 1993 only one variety was used (Table 4.1). A wide range of N-levels were applied ranging from 0 to 400 kg ha^{-1}. Application was in various split dressings, totalling 17 treatments (Wopereis *et al.*, 1994). From all experiments leaf N data were available.

In India (Thanjavur, Tamil Nadu (11° 00' N)) two experiments were conducted on the timing and rate of N application. The first experiment (IndW) was in the 1991-1992 wet season, the second one (IndD) in the 1992 dry season. The varieties were CR1009 and IR64 in IndW and IndD, respectively. In IndW, urea was used as N source in nine split N treatments, while in IndD various types of organic amendments were tested. Leaf N was measured in both experiments (Sivasamy *et al.*, 1994).

Two experiments were conducted in the Camargue region (43° 18' N) in the South of France. The experiment of 1989 (Fr89) consisted of a control and the application of 160 kg N ha^{-1} in various split dressings. Two types of N fertilizer were used: prilled urea and controlled release urea (CRU). In the experiment of 1990 (Fr90) N rates of 0, 50, 100 and 150 kg N ha^{-1} were applied before flooding using a CRU-fertilizer. In both experiments only total shoot N content was measured. Therefore, leaf N was derived from shoot N by multiplication with a constant leaf-crop N ratio of 0.55 derived from our experimental data (data not published). Because N is translocated from leaves to grains after flowering (Norman *et al.*, 1992; Penning de Vries *et al.*, 1988), a daily translocation rate of N was calculated by multiplying the daily growth rate of the crop after flowering with the final average N fraction in storage organs, i.e. 0.012. Actual leaf N content followed from substraction of total leaf N with the amount of exported leaf N.

In all experiments periodic harvests were carried out to determine dry weight and N content. The 10 experiments represent a wide range in radiation patterns (Fig. 4.1), crop, soil

Table 4.1 Overview of all experiments used in calibration and testing of the model NGROW-RICE. Acronyms as used in the text. Hybrid varieties are F1 lines of hybrid rice. *Ind.* and *jap.* indicate *indica* and *japonica* rice species. IR* is the abbreviation of the semi-dwarf *indica* rice line IR58109-113-3-3-2.

Location, Country	Acronym	Month/Year of planting	Variety	Growth duration input (d)	Range of total N ($kg\ ha^{-1}$)	Number of treatments
Jiangxi, China	Ch88a	April 1988	Hybrid V49	83	0-225	7
Jiangxi, China	Ch88b	July 1988	Hybrid V64	83	0-225	9
Jiangxi, China	Ch89	April 1989	Hybrid V49	85	150	7
Thanjavur, India	IndW	Sept. 1991	CR1009 (*ind.*)	128	0-250	9
Thanjavur, India	IndD	July 1992	IR64 (*ind.*)	93	0-125	6
Los Banos, Phil's	Ph91W	July 1991	IR*/IR72 (*ind.*)	108	0-110	6
Los Banos, Phil's	Ph92D	Jan. 1992	IR*/IR72 (*ind.*)	112	0-225	6
Los Banos, Phil's	Ph93D	Jan. 1993	IR72 (*ind.*)	106	0-400	17
Camargue, France	Fr89	April 1989	Lido (*jap.*)	141	0-160	4
Camargue, France	Fr90	April 1990	Lido (*jap.*)	130	0-160	4

and N management (Table 4.1). In all situations, pest control and water and nutrient (other than N) management were optimal.

Results

Total leaf N in the experiment with the most diverse N treatments (Ph93), was linearly related with LAI according: LAI = 0.078 · N_l + 0.174 (n = 113; r = 0.93; γ = 0.01%). A value of 0.055 for k (Eqn. 4.1) was obtained by substituting this relation in Equation 4.5.

A linear relation with a value of 0.198 and 4.589 g CO_2 MJ^{-1} for c_1 and c_2, respectively, described best the relationship between α and $F(R_g)$, although the data showed large scatter (Fig. 4.2). A comparable relationship was previously found for corn and soybean (Norman and Arkebauer, 1991).

Simulated total crop dry matter for the three Chinese data sets (124 observations) compared favourably with the observations (Fig. 4.3a). Total crop production in the three experiments was simulated with an SOD_e of 0.46 Mg ha^{-1} for Ch88a, 0.42 for Ch88b, and 0.33 for Ch89. The scaling factor c_s was 1.40, 1.25 and 1.25 for Ch88a, Ch88b and Ch89, respectively.

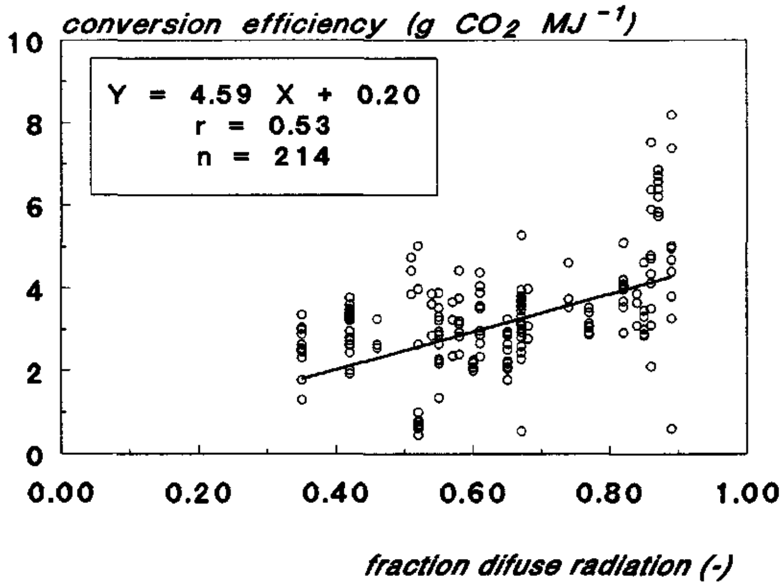

Fig. 4.2 Relationship between the fraction diffuse in the daily incident radiation and the efficiency of light energy conversion into CO_2. Symbols represent data derived from six experiments in China and the Philippines (see text).

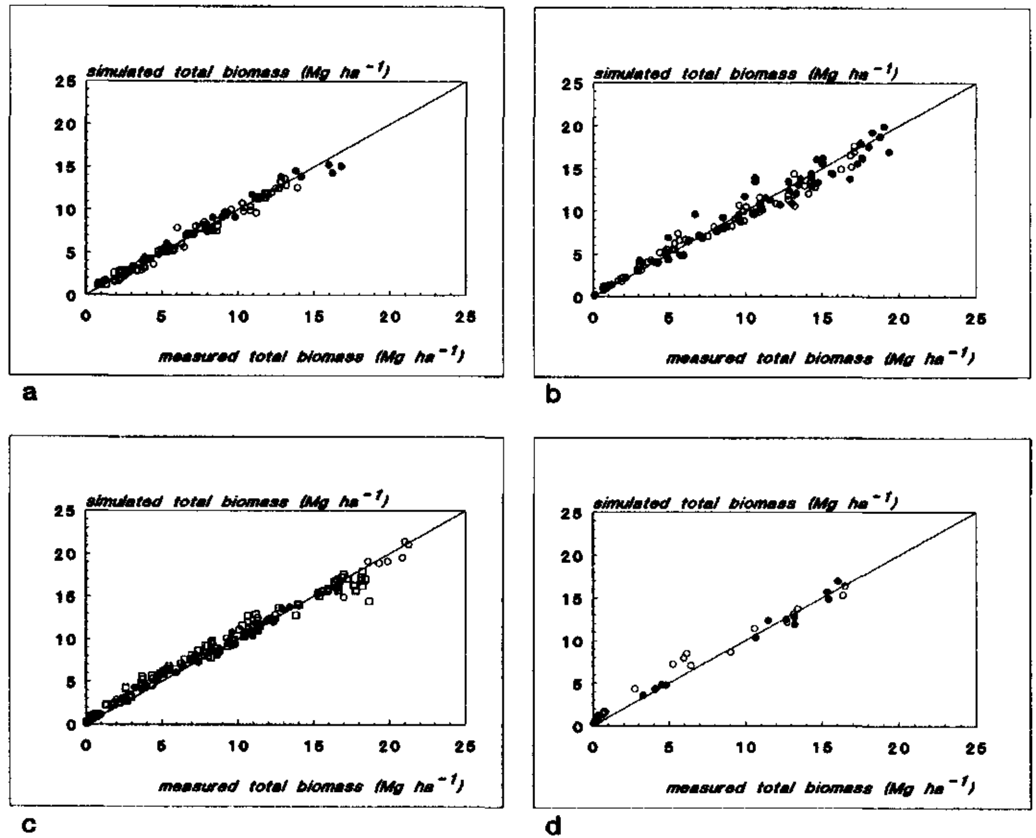

Fig. 4.3 Simulated total crop dry mass against observations for several experiments on nitrogen limited growth of irrigated rice. The solid line represents equality of simulated and observed values. a) China, Jiangxi; • = 1988 early season, ○ = 1988 late season, □ = 1989 early season. b) India, Thanjavur; • = 1991-'92 wet season, ○ = 1992 dry season. c) Philippines, Los Banos; • = 1991 wet season, ○ = 1992 dry season, □ = 1993 dry season. d) France, Camargue; • = 1989, ○ = 1990.

The simulated values of total crop dry mass for the two experiments in India showed reasonable agreement with the 138 observations (Fig. 4.3b). Variation was largest for the wet season experiment. The value of c_s was 1.30 for both experiments. SOD_e was assessed at 0.76 Mg ha^{-1} for IndW and 0.57 for IndD.

For the Philippines, 220 data points were available from the three experiments. Values for c_s were assessed at 1.05, 1.32 and 1.35 for Ph91W, Ph92D and Ph93D, respectively. The difference in the values for c_s between the wet and dry seasons is remarkable. Total crop production in the three experiments was adequately simulated (Fig. 4.3c) with SOD_e values of 0.26 Mg ha^{-1} for Ph91W, and 0.89 and 0.57 for Ph92D and Ph93D, respectively.

For Fr89 and Fr90, c_s was set at 1.00 and 1.30, respectively. Simulated production values agreed reasonably well with the observations (n = 40) in both experiments (Fig. 4.3d). SOD_e was 0.48 Mg ha^{-1} for Fr89 and 0.85 for Fr90.

Simulated maximum crop growth rates ranged from 157 to 349 kg DM ha^{-1} d^{-1}, while total biomass production was estimated between 8.28 and 21.45 Mg ha^{-1} (Table 4.2). These ranges cover the production figures normally encountered in irrigated rice.

Table 4.2 Overview of some output for all experiments used in calibration and testing of the model NGROW-RICE. Acronyms as used in the text.

Acronym	Range of simulated maximum growth rates per experiment (kg ha^{-1} d^{-1})	Range of simulated final biomass yield per experiment (Mg ha^{-1})	Absolute Simulation Observation Difference per experiment (Mg ha^{-1})
Ch88a	286 - 338	11.73 - 15.16	0.52
Ch88b	194 - 274	8.83 - 13.88	0.43
Ch89	280 - 288	11.47 - 11.92	0.31
IndW	219 - 275	13.41 - 19.82	0.66
IndD	210 - 328	9.75 - 17.61	0.68
Ph91W	157 - 221	8.28 - 13.39	0.31
Ph92D	258 - 347	10.77 - 21.45	0.64
Ph93D	234 - 349	9.77 - 17.59	0.66
Fr89	233 - 272	12.31 - 16.90	0.49
Fr90	201 - 306	8.65 - 16.40	0.90

Discussion

The current model has a number of salient features. The input requirement is low and all inputs are generally measured in agronomic experiments. The model is simple to calibrate, because of the limited number of relationships used, and after calibration, it adequately describes N limited growth of irrigated rice. NGROW-RICE has also its limitations.Temperature and daylength effects are not treated, which implies that crop production can only be adequately simulated for photo-insensitive varieties in environments with non-limiting temperature conditions for production. Furthermore, the scaling factor c_s has to be identified by calibration.

Growth rate in the model is affected by: i) the incident radiation determining the light interception at identical levels of N_l (Eqn. 4.1); ii) total leaf N content, leading to variation in light interception (Eqn. 4.1); iii) the fraction diffuse light in the incident radiation, resulting in variation in CER at identical levels of intercepted radiation (Eqn. 4.3), and; iv) crop specific and/or environmental conditions affecting the value of c_s.

No systematic trend between crop or environmental parameters and the value of c_s was found. The values varied substantially between the wet and dry seasons in the Philippines, but were similar for both seasons in India. For France, c_s differed substantially between both seasons, despite the use of the same variety. Among treatments, N effects on leaf photosynthesis (e.g. Kisthitani *et al.*, 1972; Shieh and Liao, 1987) and on assimilate or N partitioning within crops could have existed, but because an identical value for c_s could be used throughout all treatments of an experiment, its value seems mainly determined by environmental conditions particular to each experiment.

The maximum value of the energy conversion factor α is obtained by measuring the efficiency with which red light can be converted to chemical energy. This quantum yield is normally measured with green leaf tissue at low irradiance (Ehleringer and Björkman, 1977). Evans (1987) cited an average quantum yield of 24.42 g CO_2 MJ^{-1} red light for leaves of C_3 species. McCree (1972) reported an average of 24.86 g CO_2 MJ^{-1} red light. For sunlight, these figures need to be corrected with 0.85 because the fraction photosynthetic active radiation (PAR) absorbed by leaves is obtained by integrating over the whole spectrum from 0.4 to 0.7 µm (Monteith, 1972; Evans, 1987). Additionally, it has to be taken into account that sunlight contains 50% PAR on average. With these corrections an average quantum yield of 10.48 g CO_2 MJ^{-1} absorbed global radiation is obtained for C_3 species.

Temperature may significantly influence quantum yield; Ehleringer and Pearcy (1983) found for leaves of *Avena sativa* at 15°C a quantum yield of 16.28 g CO_2 MJ^{-1} red light, while it was 9.24 g CO_2 MJ^{-1} red light at 35°C. Another source of variation in quantum yield is introduced when converting from red light to sunlight, because the fraction PAR may vary between 0.42 and 0.60 (Goudriaan, personal communication). Hence, estimates of quantum yield may importantly deviate under non-controlled circumstances, which explains why in the model the scaling factor had to be adapted to each environment.

At the crop level, quantum yields are normally lower than those cited for individual leaves at optimal N supply because of the influence of leaves of sub-optimal age and N content. Both factors affect the photosynthetic capacity of leaves. Evans and Farquhar (1991) estimated the average quantum yield for a wheat crop at 2.36 g CO_2 MJ^{-1} red light, equivalent to 1.00 g CO_2 MJ^{-1} absorbed global radiation. A value of 1.96 g CO_2 MJ^{-1} absorbed global radiation was derived from Goudriaan (1982) who related gross CO_2 assimilation to PAR on clear days. This value is almost constant over latitudes ranging from the equator to 60° N. For overcast days an average quantum yield of 4.6 g CO_2 MJ^{-1} absorbed global radiation was derived from Goudriaan (1982).

These data suggest that α roughly ranges between 1 and 5 g CO_2 MJ^{-1} absorbed global radiation, the largest part of the variation originating from differences in diffuse radiation (c.f. Goudriaan, 1982; Norman and Arkebauer, 1991). The values for α used in NGROW-RICE correspond to these values. The remaining part of the variation in α was accounted for by using the scaling factor.

An indication of the expected simulation error associated with application of the model was provided by the SOD. Also, the graphical presentation of simulation results against observations gives information on model performance. The relatively low values for SOD_e warrant the conclusion that after calibration of c_s, simulation was satisfactory for all experiments. It is noticed that observations were not corrected for sampling errors.

The results from NGROW-RICE demonstrate that relatively simple mechanistic equations may be used to describe N limited crop production. Undoubtedly, simplification generates additional questions, but this need not be *a priory* a negative aspect. Some questions that, on the basis of this study, may deserve additional attention are: i) is it possible to replace the scaling factor c_s by a crop temperature effect on the energy conversion efficiency?; ii) to what extent would model outcome improve when leaf N concentrations are considered in addition to total leaf N?; iii) how sensitive is the model to changes in input and model-parameter values; iv) what is the cost, in terms of output accuracy, of replacing time series of leaf N as input, with calculated N uptake?

Some of these points will be worked out in an companion paper in which NGROW-RICE is combined with the model ORYZA_0 (Ten Berge *et al.*, 1994) to optimize fertilizer N strategy for direct seeded rice.

Chapter 5

Sensitivity analysis with NGROW-ORYZA, a model to assess optimum nitrogen application to irrigated rice.

Abstract As a tool for optimizing nitrogen (N) management in rice, a simple model was developed that simulates crop growth as function of timing and amount of applied fertilizer N. With this model two methods of fertilizer application were studied: a continuous supply of N through time, and application of N at discrete moments in time. First, standard values for the model variables were derived from an experiment on direct seeded rice in the Camargue in the South of France. Using these values, logistic cumulative N application curves that resulted in maximum crop production were assessed for different levels of total N input. Subsequently, crop production was simulated over 20 years. At each of the N levels a parameter sensitivity test was carried out to determine for which parameter changes the model was most sensitive. Simulated crop production under continuous N application was mostly affected by a factor representing local environmental effects on crop growth. The influence of cumulative seasonal radiation level on production as assessed for 20 years was small. Light interception was positively related to radiation level, but negatively to radiation-use efficiency (g MJ^{-1}). At identical N input levels optimization of continuous N application did not have a great impact on total dry matter production. Assuming application of N at discrete moments in time, simulation was carried out for 70 combinations of N doses and timing over 20 years, using total crop production and the apparent N recovery (kg N uptake per kg N applied) as criteria. Maximum production was obtained with application of 200 kg N ha^{-1} in three splits; 50% around the onset of tillering, and 25% at panicle initiation and heading, respectively. At lower levels of total N input, highest production was realized when most of the N was applied at tillering and the remaining fraction at panicle initiation. Simulated N recoveries ranged from 0.02 to 0.51.

Introduction

A widely accepted technique in the process of model evaluation is sensitivity analysis. This technique permits to systematically analyze the effect of changes in parameter values on model output, which on the one hand provides indications on the robustness of a model, and on the other hand may be used for guiding future research. A model is called robust, if model output is insensitive to small (± 10%) changes in model parameter values, while sensitivity to the values of certain parameters suggests that greater accuracy in parameter estimation would most improve model performance (Swartzman and Kaluzny, 1987).

In this paper, a sensitivity analysis is presented for all variables used in a model on nitrogen (N) limited growth of irrigated rice. The model is a combination of two previously published models, NGROW-RICE and ORYZA_0 (Stutterheim *et al.*, 1994a; Ten Berge *et al.*, 1994).

NGROW-RICE is a simple mechanistic model that calculates growth of irrigated rice on a daily basis. In this model, the effect of N on crop production is accounted for by relating light interception to total leaf N. The model has been calibrated using data sets from various experiments widely varying in weather, soil conditions, crop management and varieties, and the results demonstrated that the model can adequately be used to simulate N-limited rice production (Stutterheim *et al.*, 1994a).

Also ORYZA_0 can be used to simulate biomass production of irrigated rice under N-limited conditions (Ten Berge *et al.*, 1994). A distinct difference with the previous model is that in ORYZA_0 the soil N supply and crop N demand are treated explicitly. N supply is defined as the sum of natural soil supply and a hypothetical daily fertilizer N application. In the optimal case, the supply just meets the crop N demand. Crop N demand is not a well defined concept, but it can be treated as the final result of various processes limiting N uptake arising from the current state and growth rate of a crop, i.e. those limitations not directly resulting from low N availability in the bulk root zone (Ten Berge *et al.*, 1994). Also ORYZA_0 satisfactorily simulated crop production for various environments.

In the present study, the option from ORYZA_0 to simulate N uptake as function of N management, soil characteristics and state of the crop was combined with the clear description of light-use and N-limited crop growth from NGROW-RICE. The combination of both models is referred to as NGROW-ORYZA.

Performance of NGROW-ORYZA is evaluated for two distinctly different methods of fertilizer N application: continuous application, comparable to fertigation in protected cultures (although hypothetical), and discrete application in time. Assuming continuous N application first, the model sensitivity for changes in parameter values and for changes in the curve representing the continuous N application was assessed. Assuming discrete N application - at present the common way of fertilizer application - a new approach is proposed to develop a fertilizer N management recommendation. All analyses were carried out for direct seeded irrigated rice in the South of France.

Material and methods

General model description

The description of N limited dry matter (DM) production in NGROW-ORYZA is identically treated as in NGROW-RICE (Stutterheim *et al.*, 1994a), based on three principal relations: 1) that between total leaf N (kg ha^{-1} soil) and daily intercepted radiation (R_i in J m^{-2} d^{-1}), 2) that between R_i and daily canopy assimilation rate (CER in g CO_2 m^{-2} d^{-1}) and, 3) that between CER and daily crop growth rate.

The basic growth variables used in the model (Table 5.1) are: a scaling factor (c_s) to adapt the level of energy conversion to the specific environmental conditions; a light extinction factor (k); and two variables related to the partitioning of N in the crop, i.e. the final fraction of N in grains (F_{Ng}) and the amount of leaf N relative to total crop N during the vegetative phase (q_{Nlc}). For more information reference is made to Stutterheim *et al.* (1994a).

Crop N demand is treated as in ORYZA_0 (Ten Berge *et al.*, 1994). Daily demand can be limited by (Table 5.1): maximum crop N concentration ($F_{Nc,max}(t)$), maximum N concentration in newly formed biomass ($F_{Nc,new}$), maximum amount of N that can accumulate in leaves ($N_{l,max}$), a relative uptake coefficient that is used to calculate the exponential N uptake at the onset of growth (r_{Ni}), and, maximum daily N uptake rate (u_N). Furthermore, N demand is set to zero for the 10 days before maturity .

The supply of N is determined by the supply of 'native' soil N and N derived from fertilizers. Daily uptake rate of 'native' soil N is defined as total N uptake from non-fertilized plots (N_{som}) divided by the number of field days up to 10 days before harvest. Daily fertilizer N uptake equals the difference between crop N demand and daily uptake of 'native' soil N, but may be limited by fertilizer N availability.

Application of fertilizer N can take place either continuously, or in discrete steps. Further input to the model are: the dates of sowing, heading and harvest, latitude, and daily global radiation (J m^{-2} d^{-1}). The time step of simulation is one day.

Standard values for all crop- and site-specific variables used in the model (Table 5.1) were derived from an experiment on direct seeded rice in 1989 (Fr89) in the Camargue region (43^0 18') in the South of France (Stutterheim and Barbier, 1994; Stutterheim *et al.*, 1994b), comprising four N application treatments, a control (N0), two treatments where urea N was respectively applied in two (N2) and in three (N3) splits, and a treatment in which a slow release N fertilizer was used (NS). In each treatment 160 kg N ha^{-1} was applied.

Table 5.1 Standard values of the variables used in the model NGROW-ORYZA. The values were derived from experiments in the Camargue (South of France) in 1989.

GROWTH VARIABLE	UNIT	STANDARD VALUE
c_s	-	1.0
F_{Ng}	kg kg^{-1}	0.012
$k(N_l)$	-	0.055
q_{Nlc}	-	0.55
N DEMAND VARIABLES	**UNIT**	**STANDARD VALUE**
$F_{Nc,max}(t)$	kg kg^{-1}	0.01 to 0.05
$F_{Nc,new}$	kg kg^{-1}	0.045
$N_{l,max}$	kg ha^{-1}	120
r_{Ni}	d^{-1}	0.10
u_N	kg ha^{-1} d^{-1}	5
N SUPPLY VARIABLES	**UNIT**	**STANDARD VALUE**
N_{som}	kg ha^{-1}	90
N_{Appl}	kg ha^{-1}	user defined

c_s = Scaling factor to adapt the level of energy conversion to the specific environment
$F_{Nc,max}(t)$ = Maximum N concentration of the crop as function of time
$F_{Nc,new}$ = Maximum N fraction of newly formed biomass
F_{Ng} = Final fraction of N in grains
k = Light extinction factor
N_{Appl} = Total amount of fertilizer N input
$N_{l,max}$ = Maximum amount of N that can accumulate in leaves
N_{som} = Total uptake of N originating from native soil N
q_{Nlc} = Amount of leaf N relative to total crop N during the vegetative growth phase
r_{Ni} = Relative N uptake coefficient to set the exponential N uptake at the onset of crop growth
u_N = Maximum daily N uptake rate

Continuous N-application

To represent continuous application, a logistic cumulative N application curve as function of time ($A_N(t)$) is defined, its slope representing daily N supply (Ten Berge *et al.*, 1994). The user-defined total amount of fertilizer N input determines at which point the $A_N(t)$ curve is truncated.

To assess the optimal N application curve through time at several levels of total fertilizer-N input, an optimization was carried out using an optimization procedure (Stol *et al.*, 1992) that for each relevant level of N application (0, 100, 160, 200 and 300 kg ha^{-1}) identified the $A_N(t)$ curve that resulted in maximum crop production.

To check whether the model adequately simulated crop production, model outcome was compared to the observed production for treatments N0 and NS of Fr89. At N0, the continuous N supply was from natural sources only. A continuous supply from mainly fertilizer N (slow release) is taken into account when simulating the production in NS. The other treatments in the experiment received fertilizer in fractions and were thus not considered in this check.

Three types of sensitivity analyses were carried out assuming continuous N application:

1) To examine the effect of changes in model parameter values on total crop dry mass production, a parameter sensitivity analysis (changing the standard values by 10 and 20% in either direction) was carried out at N input levels of 0, 100, 200 and 300 kg ha^{-1}. Prior to each analysis, a fixed application regime was set by optimizing $A_N(t)$ with the standard parameter set (Table 5.1). Where variables consisted of a set of tabulated values, all values were changed. The results of each of the 160 parameter changes (four N input levels, 10 variables and four values per variable) on dry matter production were expressed relative to the simulated production values in the standard run (e.g. Table 5.2).

2) For the standard data set and the optimal $A_N(t)$ curve at each of the N input levels, a sensitivity analysis for seasonal radiation level was performed using 20 years of weather data (1972-1993), collected at local weather stations in the Camargue. The data set of 1988 was incomplete and therefore not used in the analysis. For each growing season and at each N input level, cumulative values for R_i and CER were established and radiation-use efficiency (RUE in g DM MJ^{-1}) and total biomass were assessed, resulting in 320 output values (four N levels, four variables and 20 years). Each output value was expressed as a fraction of the average value of that particular variable over 20 years and plotted against the ratio of seasonal and average cumulative radiation over 20 years. This provides a measure of the change in production caused by the prevailing weather in the year of simulation.

3) As a change in one of the model parameters may imply a modification in optimum N application pattern, the effects of parameter perturbation on crop production were evaluated again with optimization of the $A_N(t)$ curve at each change. This sensitivity analysis with N optimization was restricted to: the variables for which the model was most sensitive (as derived from the parameter sensitivity analysis), the -20% and +20% deviations from the standard values, and, levels of total N input (100 and 300 kg ha^{-1}). At each single parameter change, simulated production at optimized and non-optimized N application were compared (e.g. Table 5.3).

N application at discrete moments

The $A_N(t)$ curve is not used any more when discrete N applications are mimicked. Fertilizer application is then defined by variables representing application dates and the amounts applied. Timing and quantity are then model input.

With discrete N application, two application methods are possible: basal dressing and top-dressing. The former represents incorporation of N in the dry soil a few days before sowing, the latter allows for application of N to the floodwater at different moments during the season. When applied properly, the basal dressing of N is less prone to loss than top-dressed N (Heenan and Bacon, 1989), but the N enters the system at a time when crop demand is very low. The long residence time of this basally applied N makes that total N losses can be relatively high.

After application, fertilizer N is rapidly removed from the soil through losses and uptake, each process competing for available N. Complete quantitative description of all these processes would require very detailed information on the state of the soil system in the course of the growing season, information that is normally not available. Therefore, a more pragmatic approach was adopted: assuming that competition among the various N consuming processes will result in a relatively stable average residence time ($1/c_*$) of fertilizer N in a given soil environment, the daily rate of change in fertilizer N (dN/dt) can be expressed as a positive constant fraction of the amount present (N_t). The daily change includes crop uptake of N. Hence,

$$dN/dt \qquad = c_* \cdot N_t \qquad (5.1)$$

It is assumed that daily fertilizer N uptake can not exceed dN/dt. When crop demand is lower than dN/dt, part of the fertilizer is lost from the system.

The value for c_* can be derived from the time lapse between each fertilizer application and the moment that the mineral N concentration in the soil reaches a predefined low value (e.g. < 0.5 kg ha^{-1}). As this will depend on environment and management, c_* needs to be calibrated. In this study, values for c_* have been assessed for the basal and top-dressing, separately.

With discrete N application, the model was used to assess optimal N management at various levels of total fertilizer N input. On the basis of experience, average residence times for mineral fertilizer in the soil were set at 6 and 3 days for the basal and top-dressings, respectively. These best guesses were checked by fitting crop biomass results from the standard run to observations in the treatments N2 and N3 of Fr89. This resulted in an average residence time of 6.7 days for the basal dressing and 2.9 days for all top-dressings of N.

In direct seeded rice cultivated in Europe, fertilizer N is often applied in a number of splits However, the sometimes large areas under cultivation and the required time, labour and material for field operations, restrict the number of interventions. In the Camargue, N is normally applied three times during the growing season, one basal dressing and two top-dressings, one near the onset of tillering and the other near panicle initiation.

In the optimization, five N input levels are distinguished (0, 50, 100, 150 and 200 kg ha^{-1}) and four possible application moments, corresponding to sowing at 0 days after sowing (DAS), the onset of tillering (30 DAS), panicle initiation (60 DAS) and heading (90 DAS). At each application, 50 kg N ha^{-1}, or a multiple of that amount, could be applied. Simulation of crop production was performed for all possible combinations of N doses and timing at each level of N input. Hence, at a level of 50 kg N ha^{-1}, four different fertilization schedules were formulated, and 35 at 200 kg N ha^{-1}. In total, 70 N application combinations were evaluated (Table 5.4).

For each of the 70 combinations, total crop production and apparent N-recovery (ANR in kg N uptake per kg N applied) were simulated over 20 years. To identify the fertilizer schedule that performed best in terms of crop production and ANR, statistical analysis was carried out per N input level, using the procedure ANOVA with the Duncan multiple range test for the comparison of means (SAS, 1989). The use of the analysis of variance was justified by the independency between predicted means and residuals (data not shown).

Results and Discussion

Continuous N application

Calibration of model parts has been carried out previously (Stutterheim *et al.*, 1994a; Ten Berge *et al.*, 1994) and therefore was omitted in this study. Standard values for the model variables were acquired from the experiment in 1989. These standard values, or their range for tabulated variables, are summarized in Table 5.1.

Subsequently, the optimal continuous $A_N(t)$ curve per input level was established (Fig. 5.1). To obtain maximum production at N input levels up to 160 kg ha^{-1}, most of the fertilizer had to be applied before 60 DAS. This pattern changed at higher input levels; at a total input of 200 kg N ha^{-1}, maximum production was obtained when cumulative application at 60 DAS was only 50% of total input. Hence, at higher N input levels a more even distribution of fertilizer N throughout the growing season leads to higher biomass production.

Simulated crop production with optimized N application compared favourably with observed values at N0 and NS of Fr89, despite some overestimation for NS during the grain

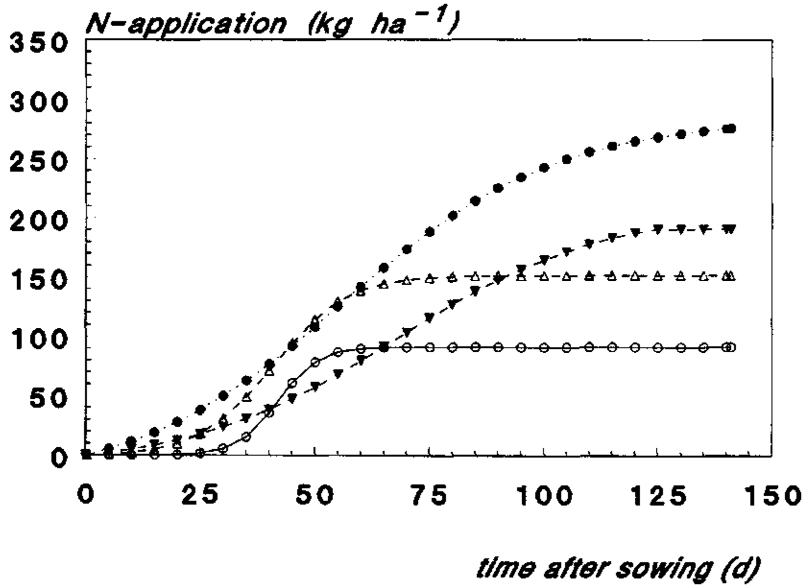

Fig. 5.1 Continuous nitrogen (N) application curves leading to simulated maximum total dry mass production of a standard rice crop grown in the Camargue. The different levels of total N input are: ∘ = 100 kg N ha^{-1}; ▴ = 160 kg N ha^{-1}; ▾ = 200 kg N ha^{-1}; • = 300 kg N ha^{-1}.

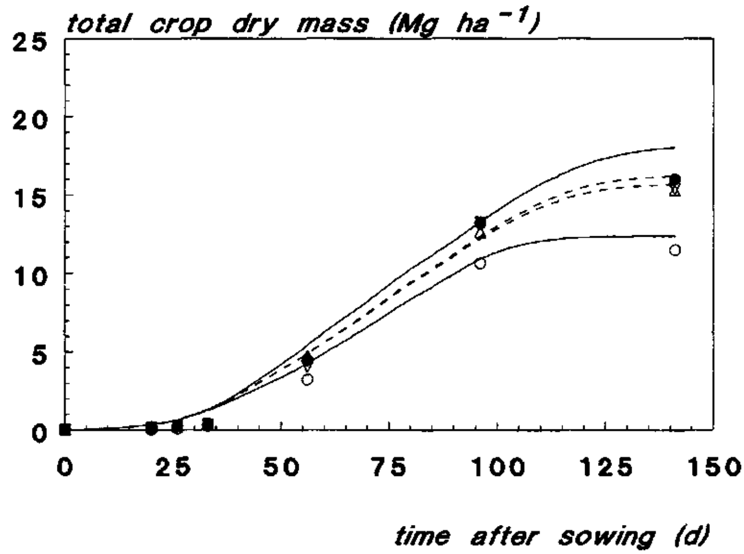

Fig. 5.2 Simulated (lines) and observed (symbols) crop production in an experiment in the Camargue. Solid lines represent acquired results with an assumed continuous N application through time. Broken lines are simulation results that were obtained assuming N application at discrete moments during the growing season. Experimental treatments were: ∘ = N0; ▿ = N2; ▵ = N3; • = NS (see text).

filling phase (Fig. 5.2). The latter suggests that in reality N supply was not optimal during this phase, which may be related to the type of slow release fertilizer used. According to factory specifications, the duration of slow release was three months at 25°C, which corresponds to the time between sowing and heading in Fr89. As pre-heading simulation was reasonably accurate, N limitation during the grain filling stage may have existed.

The results of the parameter sensitivity analysis for the four N input levels (Table 5.2) indicate that effects of changes in values of individual variables may vary among N-levels. This is most obvious for N_{som}, the total amount of 'native' soil N taken up by the crop, due to the increasing dependency of production on fertilizer N with higher input levels. Possible other effects of soil organic matter on production were not considered in the model.

Model results appeared most sensitive to changes in the values of the scaling factor c_s and the N distribution ratio q_{Nlc} (Table 5.2), while sensitivity was small or not existent for changes in all other variable values. The changes in the values for the scaling factor, which is mainly needed to account for local variation in energy conversion efficiency (Stutterheim *et al.*, 1994a), had the largest influence on crop production. A more detailed mechanistic treatment of the processes underlying these two variables is required to make the model universally applicable.

The sensitivity analysis for seasonal radiation level revealed a weak response of production at all N input levels to changes in total radiation (Fig. 5.3a), as a result of the fact that the conversion from intercepted light to photosynthetic energy depends on the fraction diffuse radiation (c.f. Stutterheim *et al.*, 1994a). Diffuse radiation is negatively related to daily incident radiation (Goudriaan, 1982). The values for RUE that were calculated in this analysis (Fig. 5.3d) agree with those reported for rice (c.f. Sinclair and Horie, 1989).

The simulated relation between application rate and maximum production represents the fertilizer response curve. An average curve was established for 20 years (Fig. 5.4). The upper curve indicates that with continuous N application production increased importantly in the application range from 0 to 100 kg N ha^{-1}. Average maximum production, represented by the asymptotic value, was around 20 Mg ha^{-1}. Assuming a harvest index of 0.42 (a value measured in Fr89), an average grain yield of 8.4 Mg ha^{-1} would be a maximum for the considered variety.

Agronomic efficiency, i.e. grain yield increase per kg of N applied, is estimated at 25, 15 and 10 kg kg^{-1} at 100, 200 and 300 kg applied N ha^{-1}, respectively. These findings agree reasonably well with experimental data from the Camargue region (Barbier, personal communication).

In the sensitivity analysis with N optimization, $A_N(t)$ curves at two N input levels were optimized at each change of the values of the variables to which model performance was most sensitive (i.e. c_s, q_{Nlc}, r_{Ni}, F_{Ng}, k and $F_{Nc,max}(t)$). Simulated production differences between

Table 5.2 Simulated total crop production at different values of single variables, expressed relative to the standard production. Standard production was assessed with all variables at their standard value as obtained from calibration. Single variables were set at -20, -10, +10 and +20% of their standard value.

	c_s	FN_g	$k(N_1)$	q_{N1c}	$F_{Nc,max}(t)$	$F_{Nc,new}$	$N_{1,max}$	r_{Ni}	U_N	N_{som}
N application level: 0 kg ha^{-1}; Standard production 11.853 Mg ha^{-1}										
-20%	***0.85***	*1.07*	*0.92*	***0.86***	1.00	1.00	1.00	***0.90***	1.00	***0.90***
-10%	*0.93*	1.03	0.96	*0.93*	1.00	1.00	1.00	0.96	1.00	*0.95*
+10%	*1.07*	0.97	1.03	*1.06*	1.00	1.00	1.00	1.03	1.00	1.04
+20%	***1.14***	*0.95*	*1.06*	***1.12***	1.00	1.00	1.00	*1.06*	1.00	*1.08*
N application level: 100 kg ha^{-1}; Standard production 17.717 Mg ha^{-1}										
-20%	***0.80***	*1.07*	*0.93*	***0.87***	*0.93*	1.00	1.00	*0.90*	0.97	0.98
-10%	***0.90***	1.03	0.97	*0.94*	0.97	1.00	1.00	0.95	0.98	0.99
+10%	1.07	0.97	1.02	*1.05*	1.00	1.00	1.00	1.04	1.01	1.01
+20%	***1.13***	*0.94*	*1.03*	***1.09***	1.00	1.00	1.00	1.05	1.01	1.02
N application level: 200 kg ha^{-1}; Standard production 18.972 Mg ha^{-1}										
-20%	***0.78***	*1.04*	*0.93*	***0.86***	*0.91*	1.00	1.00	*0.92*	1.00	0.99
-10%	***0.89***	1.02	0.97	*0.94*	0.96	1.00	1.00	0.96	1.00	1.00
+10%	***1.10***	0.97	1.03	*1.05*	1.02	1.00	1.00	1.03	1.00	1.00
+20%	***1.20***	*0.94*	*1.05*	*1.08*	1.04	1.00	1.00	*1.05*	1.00	1.00
N application level: 300 kg ha^{-1}; Standard production 19.264 Mg ha^{-1}										
-20%	***0.78***	1.04	*0.94*	***0.86***	*0.91*	1.00	1.00	*0.93*	1.00	1.00
-10%	***0.89***	1.03	0.97	*0.94*	0.96	1.00	1.00	0.97	1.00	1.00
+10%	***1.10***	0.98	1.03	1.05	1.03	1.00	1.00	1.04	1.00	1.00
+20%	***1.20***	*0.94*	1.05	*1.08*	*1.04*	1.00	1.00	*1.06*	1.00	1.00

Figures printed in bold and italic represent a relative change of more than 10%. Figures in italic represent changes between 5 and 10%. Other printed figures represent changes of less than 5%.

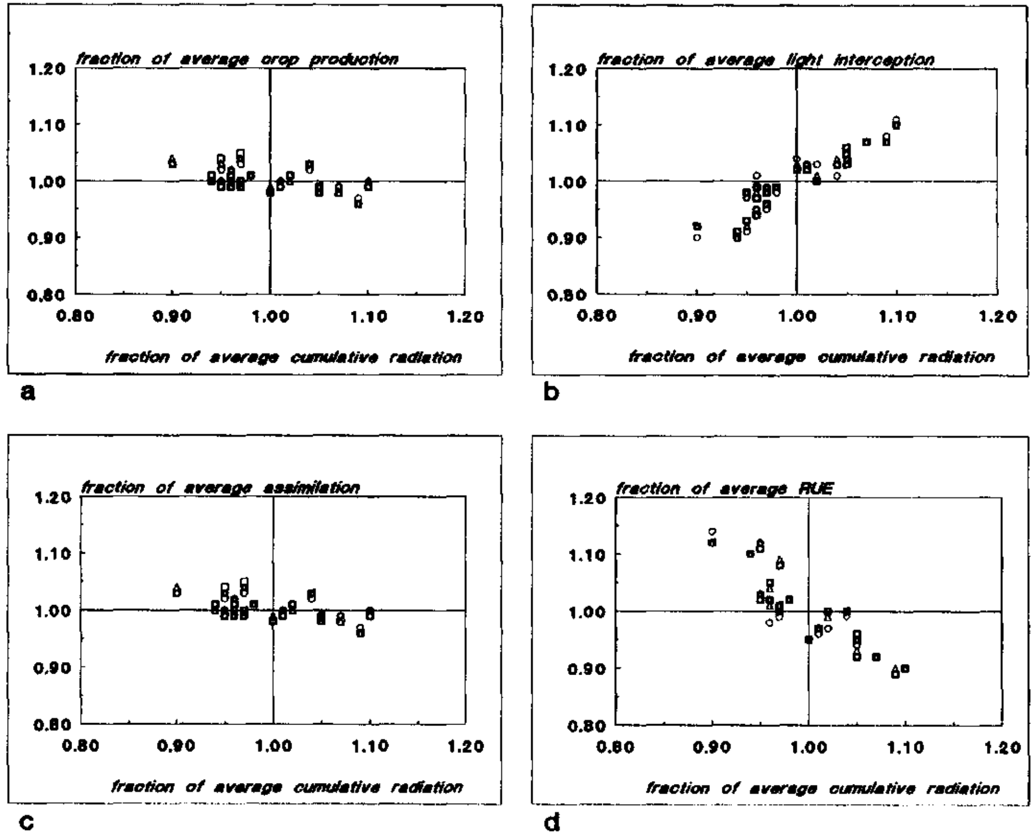

Fig. 5.3 Model variable values at four levels of total N input as function of variation in cumulative seasonal radiation. On both scales the values are expressed as fraction of the 20 years average of the considered variable. ∘ = 0 kg N ha^{-1}; ▵ = 100 kg N ha^{-1}; ◊ = 200 kg N ha^{-1}; □ = 300 kg N ha^{-1}. The variables represent a) total seasonal dry matter production (kg ha^{-1}), b) total seasonal amounts of intercepted light (J m^{-2}), c) total carbon exchange during the growing season (mg CO_2 m^{-2}), and d) average seasonal radiation-use efficiency (g MJ^{-1}).

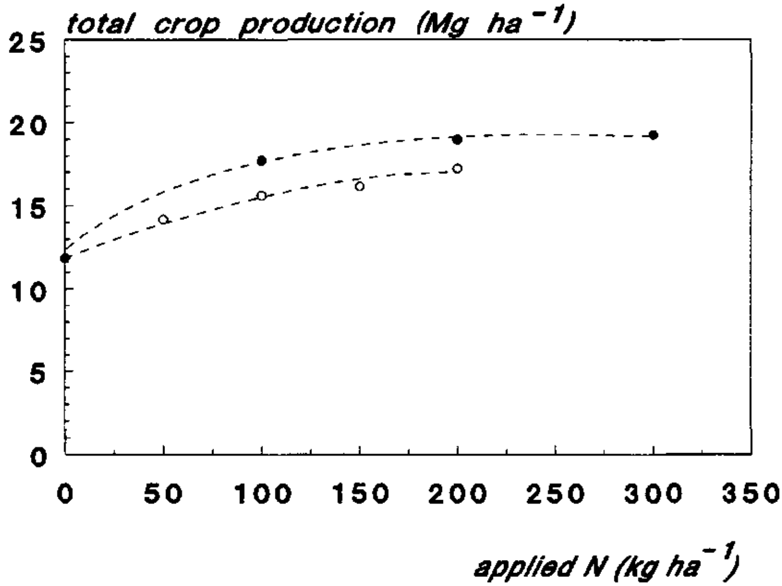

Fig. 5.4 Simulated maximum total crop production of a standard rice crop grown in the Camargue at different levels of total fertilizer N input. Results are 20 years averages. ∘ = assuming N application at discrete moments during the growing season; • = assuming continuous N application through time.

optimized and non-optimized conditions were within an interval of 50 to 100 kg DM ha^{-1} at all input levels (Table 5.3), indicating that total crop production hardly improved with further refinement of continuous fertilizer N application.

Optimization of N application for the standard run demonstrated that fertilizer N management has to be a function of the total amount of N applied. Optimal fertilizer strategy distinctly changed at N input levels higher than 160 kg ha^{-1}. This N level may reflect the maximum quantity of N that can be taken up by the crop during the exponential and linear growth phases. When the supply exceeds this quantity, total crop production is apparently more promoted by distributing the fertilizer N evenly throughout the growing season.

N application at discrete moments

Simulation for 20 years, for each of the 70 different fertilization strategies (Table 5.4), resulted in a maximum crop production of 17.2 Mg ha^{-1} at a N input level of 200 kg ha^{-1} applied in three splits: 100 at 30 DAS and 50 kg N ha^{-1} at 60 and 90 DAS, respectively (Table 5.4). The finding that fertilizer N has to be applied around heading, if total N input

Table 5.3 Simulated total crop production (kg ha^{-1}) at two N application levels, without (n.o.) and with (opt.) optimization the logistic cumulative N application curve $A_N(t)$. Simulation was with individual variable values set at -20% or +20% of their standard value.

100 kg N ha^{-1}

	-20% n.o.	-20% opt.	+20% n.o.	+20% opt.
c_s	14111	14092	19993	20758
k	16539	16562	18240	18510
$F_{Nc,max}(t)$	16456	16462	17717	18378
FN_g	18896	19042	16663	16618
q_{N1c}	15402	15475	19329	19638
r_{Ni}	15904	15972	18633	19256

300 kg N ha^{-1}

	-20% n.o.	-20% opt.	+20% n.o.	+20% opt.
c_s	15052	15063	23267	23508
k	18020	17988	20176	20221
$F_{Nc,max}(t)$	17467	17510	20113	20225
FN_g	20067	20077	18164	18182
q_{N1c}	16637	16674	20746	20782
r_{Ni}	17933	17952	20508	20504

For variable abbreviations see Table 1

is high, is a rather new aspect for the Camargue and needs experimental confirmation.

Highest crop production at the other N levels was generally realized when the main part of the total amount of fertilizer N input was applied at 30 DAS, and the remainder at 60 DAS. At all input levels, production was lowest when the total amount of fertilizer was applied as a basal dressing. This confirms the conclusion of regional research in the Camargue that in case of basal N dressing, only small amounts (maximally 50 kg ha^{-1}) should be applied.

The increase in crop production with increasing levels of split applied N was clearly less than under continuous application of N (Fig. 5.4). With a harvest index of 0.42, average

Table 5.4 Simulated total crop dry mass (TDM in Mg ha^{-1}) and apparent N recovery (NREC in kg kg^{-1}) at different levels of total N input. Timing of fertilizer N application (kg ha^{-1}) before sowing (t0) and/or at 30 (t1), 60 (t2) and 90 (t3) days after sowing. Identical letters at each N level indicate no significant differences ($\gamma = 0.05$).

N application: 0 kg ha^{-1}

t0	t1	t2	t3	TDM	NREC
0	0	0	0	***11.853***	-

N application: 50 kg ha^{-1}

t0	t1	t2	t3	TDM	NREC
0	0	0	50	13.008^{a}	***0.51***^{a}
0	0	50	0	13.495^{b}	***0.51***^{a}
0	50	0	0	***14.204***^{c}	0.39^{b}
50	0	0	0	*12.101*^{d}	*0.03*^{c}

N application: 100 kg ha^{-1}

t0	t1	t2	t3	TDM	NREC
0	0	0	100	13.311^{a}	0.33^{a}
0	0	50	50	14.627^{b}	***0.51***^{b}
0	0	100	0	13.862^{c}	0.33^{a}
0	50	0	50	15.344^{d}	0.45^{c}
0	50	50	0	***15.620***^{e}	0.45^{c}
0	100	0	0	14.800^{f}	0.26^{d}
50	0	0	50	13.255^{g}	0.27^{e}
50	0	50	0	13.721^{h}	0.27^{e}
50	50	0	0	14.438^{i}	0.21^{f}
100	0	0	0	*12.257*^{j}	*0.03*^{f}

N application: 150 kg ha^{-1}

t0	t1	t2	t3	TDM	NREC
0	0	0	100	13.482^{a}	0.24^{a}
0	0	50	100	14.919^{b}	0.39^{b}
0	0	100	50	14.982^{c}	0.39^{b}
0	0	150	0	14.061^{d}	0.24^{a}
0	50	0	100	15.640^{e}	0.35^{c}
0	50	50	50	16.714^{e}	***0.47***^{d}
0	50	100	0	15.954^{f}	0.35^{ce}
0	100	0	50	15.931^{f}	0.34^{e}
0	100	50	0	***16.160***^{g}	0.34^{e}
0	150	0	0	15.119^{h}	0.20^{f}
50	0	0	100	13.557^{i}	0.23^{g}
50	0	50	50	14.850^{j}	0.35^{h}
50	0	100	0	14.084^{d}	0.23^{g}
50	50	0	50	15.575^{k}	0.31^{i}
50	50	50	0	15.836^{l}	0.31^{i}
50	100	0	0	15.022^{m}	0.19^{j}
100	0	0	50	13.429^{n}	0.19^{k}
100	0	50	0	13.880^{o}	0.19^{k}
100	50	0	0	14.587^{p}	0.15^{l}
150	0	0	0	*12.416*^{q}	*0.02*^{m}

N application: 200 kg ha^{-1}

t0	t1	t2	t3	TDM	NREC
0	0	0	200	13.599^{a}	0.20^{a}
0	0	50	150	15.083^{b}	0.31^{b}
0	0	100	100	15.270^{c}	0.33^{c}
0	0	150	50	15.175^{dp}	0.31^{b}
0	0	200	0	14.196^{e}	0.20^{a}
0	50	0	150	15.806^{f}	0.28^{d}
0	50	50	100	16.991^{g}	***0.39***^{e}
0	50	100	50	17.028^{h}	***0.39***^{e}
0	50	150	0	16.137^{i}	0.28^{d}
0	100	0	100	16.224^{j}	0.29^{f}
0	100	50	50	***17.235***^{k}	***0.39***^{e}
0	100	100	0	16.484^{l}	0.29^{f}
0	150	0	50	16.244^{j}	0.28^{d}
0	150	50	0	16.449^{m}	0.28^{d}
0	200	0	0	15.328^{n}	0.16^{g}
50	0	0	50	13.728^{o}	0.19^{h}
50	0	50	100	15.142^{p}	0.30^{i}
50	0	100	50	15.202^{d}	0.30^{i}
50	0	150	0	14.283^{q}	0.19^{h}
50	50	0	100	15.870^{r}	0.27^{j}
50	50	50	50	16.925^{s}	0.36^{k}
50	50	100	0	16.167^{i}	0.27^{j}
50	100	0	50	16.150^{i}	0.27^{j}
50	100	50	0	16.365^{t}	0.27^{j}
50	150	0	0	15.330^{n}	0.16^{l}
100	0	0	100	13.731^{o}	0.18^{m}
100	0	50	50	15.007^{u}	0.27^{j}
100	0	100	0	14.241^{v}	0.18^{m}
100	50	0	50	15.723^{w}	0.24^{n}
100	50	50	0	15.974^{x}	0.24^{n}
100	100	0	0	15.160^{p}	0.15^{o}
150	0	0	50	13.569^{a}	0.15^{p}
150	0	50	0	14.008^{y}	0.15^{p}
150	50	0	0	14.701^{z}	0.12^{q}
200	0	0	0	*12.540*^{A}	*0.02*^{r}

Figures printed in bold italics represent maximum values per N application level, those printed in italics are minima.

agronomic efficiencies of 20, 16, 12 and 11 kg kg^{-1} were established at N input levels of 50, 100, 150 and 200 kg ha^{-1}, respectively. The 20 years average maximum yield was estimated at 7.4 Mg DM ha^{-1}.

The 20 years average N recoveries for each of the 70 possible N treatments revealed that maximum values for ANR not automatically lead to maximum crop production (Table 5.4). This may be due to other growth limiting factors than N, resulting in limited production at identical N uptake.

Conclusions

- NGROW-ORYZA can be used to test N application strategies for total crop production and for fertilizer nitrogen efficiency. Application can either be continuous through time, or it may take place in discrete steps.
- Calibration per site remains necessary with use of NGROW-ORYZA.
- Variation in the energy conversion efficiency mostly affected total crop production. Quantification of the sources of this variation should significantly improve the predictive value of NGROW-ORYZA.
- The results indicate that: i) higher biomass production takes place when fertilizer nitrogen is evenly distributed throughout the growing season; this was demonstrated for continuous applied nitrogen as well as for discrete fertilizer application, ii) the basal application of fertilizer nitrogen should be limited because of its low recovery and, iii) the maximum attainable yield in the Camargue is 8.4 Mg ha^{-1} for the representative medium growth duration variety 'Lido'.

Chapter 6

General discussion

Despite the price support policy of the European Union, European rice production does not meet the European demand for rice. This is illustrated by the fact that for several decades, Europe has imported more than 40% of the USA rice export on an annual basis (FAO, 1994). The USA was able to be the second rice exporting country of the world in 1992, after Thailand. Together, these two countries had a share of 46% of the total world rice market, only representing 2.8% of total world production. The recently endorsed General Agreement on Tariffs and Trade (GATT) may have serious consequences for European rice production, because of the increasing competition on the European rice market. Hence, the European rice industry has to strengthen its economic position to be viable.

The weak position of the European rice industry on the world market can be improved by decreasing the high costs of production caused by sub-optimal use of capital-inputs. In European rice cultivation, fertilizers and crop protection agents are abundantly used, of which a substantial part is emitted into the environment. Such losses represent financial costs for farmers and they may contribute to deterioration of the environment. Hence, an optimal use of capital-inputs is required, both from an economic and environmental point of view.

An additional incentive to optimize the use of capital-input may come from policy. The reform of the Common Agricultural Policy (CAP), accepted in June 1992 by the European Community, aims at supporting farming practices that reduce pollution (Bandarra and Baldock, 1992). One possible measure to attain this objective is to penalise a high use of capital-input per hectare, which would stimulate use-optimization (De Wit, 1994).

Hence, one of the main challenges for European rice research is to develop alternative production techniques that increase the production per unit input in rice farming, to meet the new environmental and economic requirements imposed by CAP and GATT. The present study contributes to this objective by formulating alternatives for current nitrogen (N) management in European rice farming. The methodology applied to analyze the effects of these alternative techniques on the recovery of fertilizer N and crop production is illustrated for a typical European rice producing area, i.e. the Camargue in the South of France.

Methodological aspects

The methodology developed in this study permits comparison of actual N efficiencies in rice with attainable efficiencies (Chapter 2), it provides information on the main constraints to further yield improvement (Chapter 3), and uses a model to assess an efficient fertilizer N application strategy, based on split application of non-coated urea (Chapter 4 and 5).

The most widely used nutrient in rice cultivation is N. Recovery of applied fertilizer N (De Wit, 1953) in irrigated rice normally ranges from 20 to 40% (De Datta, 1981; Vlek and Byrnes, 1986), but may be as high as 89% (Humphreys *et al.*, 1987). This variation in N recovery, combined with the observation that the utilization efficiency, i.e. the N uptake per unit grain dry mass, is rather constant under N-limited growth conditions (Van Keulen, 1977; 1982), leads to the conclusion that the agronomic efficiency, or the amount of N applied per unit grain dry mass, may also vary considerably.

As recent communications on these three indicators of fertilizer N efficiency in European rice cultivation systems were nonexistent, the present study firstly addressed the question of actual N efficiencies in those systems. Reference values for all three indicators were provided at the field, regional and continental scale (Chapter 2). Subsequently, the attainable N efficiency was assessed experimentally by using a special coated N fertilizer. The difference between attainable and actual N efficiency provides insight into the possible efficiency improvements in the near future. However, as coated fertilizer will not be widely adopted by farmers, because of its relatively high price, fertilizer strategies have to be developed that can approach the attainable N efficiency while using standard fertilizer forms like non-coated, prilled urea. An important part of this study was dedicated to this objective.

A study on growth and yield formation, as affected by N management, was carried out to increase understanding of the formation of source and sink capacity for carbohydrates of rice crops (Chapter 3). The results of that study are used to discuss the attainable yield level in the Camargue, as determined by local weather, soil conditions, and crop properties. This yield level dictates the maximum amount of fertilizer N for that should be provided to a crop.

A summary simulation model, which combine high N recovery with high crop production (Chapter 4 and 5), was used to formulate alternative N management strategies at several levels of total N input. The input requirements of the model are modest, which facilitates its use.

Finally, a tailor-made efficient N application strategy for a representative rice variety from the Camargue was provided for different levels of total N input, as a demonstration that the model can be used to formulate alternative N application strategies, and as a first assessment of more efficient fertilizer management methods for rice cultivated in Europe (Chapter 5).

Nitrogen loss

Currently, the efficiency of fertilizer N in European rice cultivation is very low. It was shown that in farmer's fields in the Camargue at most 21% of the applied N is taken up by the crop. In experiments throughout Europe this maximum recovery was only 32%. The principal question here is, how much of the applied fertilizer N is lost from the soil-plant environment? This is worked out below for the Camargue, but the approach may be applied to other rice production areas.

The fertilizer N not directly taken up by the crop partly contributes to maintenance of soil fertility, and part of it is lost from the soil-plant environment. If it is assumed that N loss is limited as long as the soil immobilizes applied N, then a critical N input level can be assessed at which the soil system is not capable any more to retain this N. The critical level depends on the capacity of the soil to immobilize applied fertilizer, and on fertilizer N recovery.

The apparent amount of fertilizer N minimally needed to replenish the natural soil N supply to crops, is deduced from crop N uptake in the absence of fertilizer application. For yields ranging from 4 to 6 Mg ha^{-1} on Camargue soils not receiving fertilizer N (Barbier, personal communication), this amount is estimated at 70 to 110 kg ha^{-1} per season, using a N utilization efficiency of 56 kg grain dry mass per kg N uptake (Chapter 2). However, part of the N supplied by the soil is derived from other sources than fertilizer, like atmospheric deposition, decomposition of crop stubbles and roots, and biological N_2 fixation. Hence, the natural N supply has to be corrected for these inputs to obtain the real contribution of fertilizer N to the maintenance of soil fertility, i.e. the amount N released by the microbial biomass in the year of production, and any N originating from the soil cation exchange complex (CEC).

The contribution of atmospheric deposition to the fertility of European rice fields may be assumed low, since, apart from the Po valley in Italy, no important sources of N emission exist near these production zones. As no data could be found on the deposition of N in the South of Europe, maximum deposition of N is set equal to quantified emissions of ammonia (NH_3) nitrogen. For the European rice production areas, these emissions were found to be less than 7 kg ha^{-1} per year, while in the Po valley 21 kg NH_3-N ha^{-1} per year is emitted (Buijsman *et al.*, 1987). The contribution of N deposition is here assumed to be 14 kg N ha^{-1} per year. Biological N_2 fixation takes place during the entire growing season, but as this N is incorporated into living non-rice biomass, it mainly becomes available through decomposition after the fields are drained. The contribution of this N to maintenance of soil fertility is negligible because of post-harvesting burning practices, by which most of plant tissue N is lost (Anderson and Poth, 1989; Kuhlbusch *et al.*, 1991). Root decay in the year of production may supply some N to the soil, but this amount does not exceed 10 kg ha^{-1} at actual production levels of rice in Europe. Identically to the non-rice biomass, the stubble is normally burned and thus hardly contributes to maintenance of soil N fertility. After correction for the resulting average contribution of 24 kg N ha^{-1} from atmospheric deposition and root decomposition, the fertilizer N supply that is minimally needed to maintain soil N fertility, is assessed at 46 to 86 kg ha^{-1} $season^{-1}$. It is noticed that the physico-chemical fixation capacity of European rice soils is insignificant due to their very low CEC. In the Camargue, CEC is generally lower than 10 meq per 100 g.

The amount of N that either is taken up from the soil system, or is lost, is presented as function of total fertilizer N input (Figure 6.1). The reaction on N input level is calculated for the two types of fertilizer tested in the Camargue: the coated fertilizer with a maximum recovery of 0.58, and the non-coated urea fertilizer with a maximum recovery of 0.21 (Chapter 2). For illustrative purposes it is assumed that these recoveries remain constant up to N application levels of 150 kg ha^{-1}, although recovery may strongly decrease at high application levels (Chapter 2).

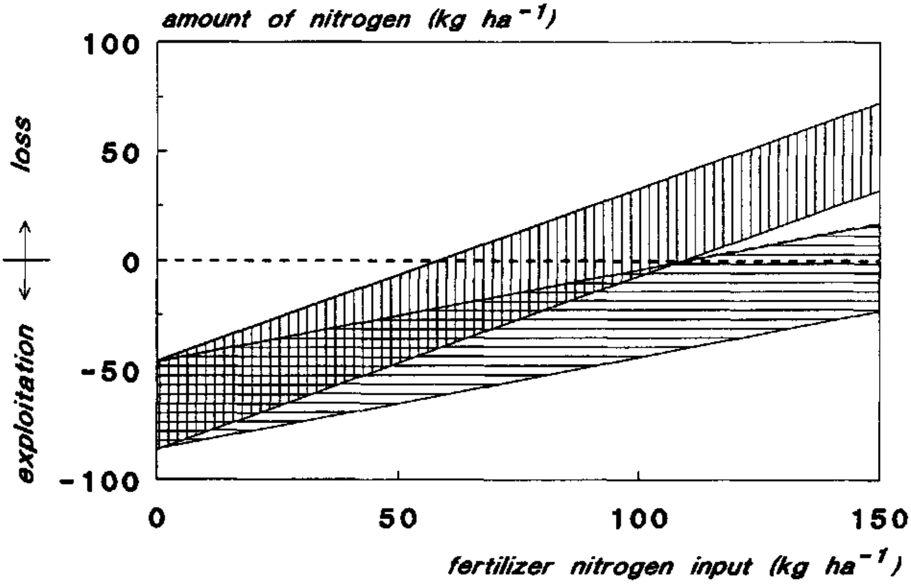

Fig. 6.1 Total fertilizer nitrogen input against the amount of soil nitrogen in excess of the sum of crop N uptake and immobilized soil N (positive ordinate), or short of this sum (negative ordinate). Hatched areas indicate the range of reaction on input of uncoated urea (vertically hatched) or resin coated urea (horizontally hatched) to Camargue soils. The upper boundary of each area represents high fertile soils, the lower boundary low fertile soils.

Figure 6.1 clearly demonstrates that a poorly recovered fertilizer (urea) may lead to N loss at relatively low levels of total fertilizer N input. For the Camargue, these levels are 58 and 108 kg N ha^{-1} for low and high fertile soils, respectively. If less fertilizer N is applied than above levels, soil fertility decreases. With coated fertilizer, 110 kg N ha^{-1} may be applied to low fertile soils without a serious risk of N loss. On the other hand, less fertilizer N remains for maintenance of the soil N fertility because of the high N recovery of this fertilizer. The risk of exploitation of soil N is thus increased. This risk is even more evident when using resin coated fertilizer on high fertile soils.

N loss is thus dependent on the rate of fertilizer N, its recovery, and the actual N fertility level of the soil. For all soil types, an increase in fertilizer N recovery is associated with a reduced risk of N loss, but an increased risk of soil fertility exploitation.

The attainable yield level and related N requirement

From the farmer's point of view, the relevant question is at which N input level a maximum yield is attained. The results presented in Chapters 3 and 5 can be used to derive this maximum attainable yield level.

The attainable capacity for carbohydrate storage during the grain filling stage is determined by the number of spikelets. Spikelets can thus be considered as sinks for carbohydrates. The plant organ(s) supplying carbohydrates for grain filling can be called source(s). N management during the pre-flowering phase of the crop can be used to establish a desired sink capacity (Matsushima, 1979). Subsequently, N supply should be sufficient to maintain the source capacity at a level equal to or higher than the sink capacity, to realize the maximum attainable yield. Hence, maximum attainable yield may be derived from the maximum attainable source capacity during the grain filling period provided sink capacity is not yield-limiting.

A combination of adequate N supply, abundant radiation and moderate temperatures is conducive to maintain the source capacity during the grain filling phase. According to the results presented in Chapter 3, an average growth rate of 150 kg ha^{-1} d^{-1} can then be expected during the grain filling phase for the medium duration variety 'Lido'. In the present study, the duration of grain filling for this variety was assessed at 45 days with ample N supply. Hence, without sink limitations a yield of 6.8 Mg ha^{-1} could be realized when carbohydrates are only provided by photosynthesis during the grain filling period. Additionally, pre-flowering photosynthesis products, stored temporarily in culms, leaves and roots, can provide up to 40% of the assimilates accumulated in grains (Yoshida, 1981). However, at high N application levels, the contribution of reserve assimilates to grain growth may be as low as

10% (Kropff *et al.*, 1993). Hence, for 'Lido' the extreme values for attainable yield would be 7.4 and 9.5 Mg ha^{-1}.

The above mentioned trade-off between the contribution of post-heading photosynthesis and translocation to grain filling may be an important constraint to further yield increase. To realize yield levels beyond the estimated attainable values, two main options exist for given genotypes: i) increasing the average crop growth rate during grain filling, and ii) extension of the grain filling period. Future rice research aiming at higher rice yields should put more emphasis on these options.

Assuming optimal N supply to the crop, the attainable yield derived from the simulation results of this study was 8.4 Mg ha^{-1} (Chapter 5), i.e. a value between the both extremes mentioned above. To realize a yield of 8.4 Mg ha^{-1} using common prilled urea with a maximum N recovery of 0.21, at least 380 kg fertilizer N has to be applied to Camargue soils with low fertility levels for N, and at least 190 kg fertilizer N to those soils having relatively high equilibrium levels. The N losses associated with such high application levels are unacceptable.

In conclusion, it can be stated that the gap between the actual rice yield levels of the Camargue (Chapter 2) and the attainable ones, has to be bridged by increasing current N recoveries. The financial saving associated with a more efficient N use is certainly an incentive for farmers to adapt their N management.

A simple model approach for N management advice

The simulation model NGROW-ORYZA was used to derive an optimal N management strategy for a crop by testing a large number of strategies. Interception and use of light are treated in a module called NGROW-RICE.

NGROW-RICE, and therefore NGROW-ORYZA, are based on the concept of maximum quantum yield, i.e. the efficiency with which red light can be converted into chemical energy by photosynthesis. Quantum yield is normally determined on individual leaves under controlled conditions. Some of the factors that affect quantum yield are: plant species, photorespiration, atmospheric CO_2 concentration, and temperature (Ehleringer and Björkman, 1977; Ehleringer and Pearcy, 1983; Evans, 1987).

To obtain the energy conversion efficiency of a crop, correction of the quantum yield is required for the ratio of photosynthetically active radiation (PAR) to total incoming radiation, and the spectral distribution within the range of 0.4 - 0.7 μm. The ratio is a function of solar elevation and atmospheric conditions, while the spectral distribution is determined by canopy structure and leaf chlorophyll content (Monteith, 1972).

Variation in energy conversion efficiency as a function of solar elevation and atmospheric conditions can be taken into account by explicitly incorporating those physical factors in a model. The effects on energy conversion originating from biological factors such as canopy structure and leaf chlorophyll content are more complicated to assess representatively, because of their large temporal and spatial variability. Identical problems exist when the variation in energy conversion efficiency is expressed as a function of photo-respiration and temperature. Instead of explicitly quantifying all these sources of variation in quantum yield and energy conversion in the model, the use of a scaling factor was proposed (Chapter 4). For a given site, cultivar and growing period, calibration of the scaling factor is only necessary for one of the treatments in an experiment on N management, by fitting simulated to observed values of total crop biomass production. Subsequently, crop production in the other N treatments can be simulated without recalibration. Various N management strategies may then be evaluated to assess an optimal strategy. Additional research is required to assess the robustness of the scaling factor with changes in cultivar, growth conditions and growing period.

Recommended N management

On the basis of the results presented in this thesis, an optimal N management recommendation for a representative medium duration rice variety in the Camargue was formulated. Fertilizer N application is most effectively applied at the onset of tillering and panicle initiation. If total N input exceeds 150 kg ha^{-1}, additional N has to be applied around heading to maintain post-heading growth rate. N recoveries may increase from the current 0.2 to 0.5, by improved fertilizer application timing. This higher N efficiency can lead to increased crop production.

Two aspects are worth mentioning. Firstly, application of N before flooding results in low N recoveries. However, in current farmer's practice, the main dose of total N input to a field is applied at that moment, because of the reasons mentioned in Chapter 1. This may be one of the reasons for the low N recoveries assessed for the Camargue. Secondly, an additional N application around heading is not common in the Camargue, although it was locally demonstrated that yields were seriously limited because of source limitations (Barbier, personal communication).

With relatively simple measures, using current fertilizer forms and techniques, rice cultivation in the Camargue and in comparable production areas can be made more environment-friendly. Furthermore, yields may be increased, applying lower amounts of fertilizer N than customary in current N management. This is a first step towards a sound and more competitive European rice industry.

Summary

Worldwide, the use of capital-input for the production of food crops increases strongly. This is the result of an increasing demand for food, and the necessity to realize higher production volumes per unit land surface because of the limited availability of arable land. The increasing use of input may have negative consequences for man and the environment if it is associated with an increasing emission of input into the environment. Moreover, losses represent financial costs. Research aiming to optimize input use is thus relevant, as well in the economical, as in the agronomical context.

The research in this thesis is on the improvement of nitrogen efficiency in irrigated rice in Europe. Three expressions were used for this efficiency: i) agronomic efficiency, representing the amount of N applied per unit harvested grain dry mass (kg kg^{-1}), ii) utilization efficiency, i.e. the N uptake per unit grain dry mass (kg kg^{-1}), and iii) recovery, or the fraction of applied nitrogen taken up by the crop (kg kg^{-1}). The study proposes alternatives for the currently inefficient management of fertilizer nitrogen in rice. A case study was carried out for the Camargue in the South of France. In this region, the use of capital-input per unit land surface is high, as is the case in most of the European rice growing areas. The research was on nitrogen. This element is the main applied nutrient in agriculture, and therefore, it's potential contribution to the degradation of the environment is significant.

Because recent data on nitrogen efficiency in European rice cultivation were lacking, previously defined expressions for nitrogen efficiency were quantified for main European production areas (Chapter 2). Firstly, a constant value of 56 kg kg^{-1} for the utilization efficiency was derived from the results of experiments conducted in the Camargue in 1989 and 1990. Values for the agronomic efficiency and the recovery were assessed for normal prilled urea and coated fertilizer (Osmocote urea). Subsequently, these experimentally determined nitrogen efficiencies for prilled urea were compared to those of the whole Camargue region, and with those derived for other Mediterranean rice production areas in Europe. Maximum agronomic efficiencies were found between 12 and 17 kg kg^{-1}. Maximum recoveries ranged from 0.21 to 0.32 kg kg^{-1}, indicating that only 21 to 32% of applied fertilizer nitrogen is found back in the crop. With the coated fertilizer agronomic efficiency was improved to 32 kg kg^{-1}, while recovery increased to 0.58 kg kg^{-1}. These improved figures can be considered as target nitrogen efficiency values for the near future. Unfortunately, current prices of coated fertilizers are high, which does not favour its general use. Therefore, the remaining part of this study treated the question of whether or not the target efficiencies could be obtained with common fertilizer forms and application techniques.

The data from the Camargue experiments were further analyzed to increase understanding on the effects of nitrogen management on growth and rice production (Chapter 3). The formation of vegetative plant parts, constituting the potential source of grain filling substances, and the capacity of grains to fill ('sink'), received special attention. Nitrogen uptake rate and crop growth rate were related to variables expressing the state of the crops during the growing season. It appeared that dynamics of nitrogen uptake rate are strongly determined by initial plant density. In a dense plant stand, available nitrogen is taken up rapidly, after which this element becomes limiting for growth if no further application of nitrogen takes place. In an open plant stand and at identical nitrogen availability, such a limitation of growth takes place later in the growing season. Hence, when developing nitrogen fertilizer strategies, the actual state of crop and soil has to be taken into account. This aspect receives additional attention. Furthermore, it was demonstrated that different fertilizer-nitrogen strategies affected the production of individual plant organs. It was concluded that the potential source capacity can be controlled with nitrogen management. However, the relationship between potential source capacity and grain yield was not always positive. One of the reasons could be that at given temperatures the relative contribution of respiration to the total carbohydrate balance of a crop increases with the amount of standing biomass. Hence, a source limited yield is possible, even when the potential source capacity is high. To reduce the risk of yield limitation, the advice given was to strive for a crop with a moderate leaf area containing a high nitrogen content. System-analytical research can be used to further quantify this advic for various production areas, seasons, and varieties.

A simple crop growth model was developed to simulate nitrogen limited growth of rice (Chapter 4), and to quantify the effect of alternative nitrogen application strategies on crop production and fertilizer nitrogen recovery (Chapter 5). Finally, a tailor-made application strategy was provided for the variety 'Lido'. It was found that fertilizer N is most effective for crop production when applied during the exponential and linear growth phases of the crop. At higher N application levels, additional N applied at heading appears most effective. This strategy combines a maximum attainable nitrogen recovery with a high crop production. Model simulation showed that a grain yield of 8.4 Mg ha^{-1} is the maximum attainable for Lido, under the production circumstances of the Camargue. In reality, this yield level is difficult to obtain because it was assumed that nitrogen was continuously applied to the crop. In practice, nitrogen is applied at discrete moments during the growing season. Hence, optimization of application strategy is only possible by varying the dose of fertilizer and the timing of application.

To formulate an appropriate recommendation for nitrogen application, 70 fertilizer management strategies were simulated for 20 growing seasons. Per level of total applied nitrogen, total dry mass production and nitrogen recovery were quantified for each strategy.

High recoveries combined with high crop production were obtained with the application of nitrogen at the onset of tillering and at panicle initiation. It was demonstrated that the recovery could increase from 0.21 to 0.51, signifying more than a doubling of the nitrogen uptake from fertilizer. Average crop production over 20 years was not inferior to that obtained in the Camargue experiments. Production increased with the amount of applied nitrogen, but this was associated with a strong decrease in nitrogen recovery. It was calculated that with nitrogen applications exceeding 150 kg ha^{-1}, the total amount of fertilizer N is most efficiently applied in three fractions: at the onset of tillering, at panicle initiation, and at heading, respectively. It was recommended that further experimental research should evaluate the advantages of a third application at heading, firstly, because in the Camargue total nitrogen applications generally exceed 150 kg ha^{-1}, and secondly, because the third application at heading is not common in this region. Simulation further shows that the recovery of nitrogen applied before sowing is very low. However, most of the nitrogen used in European rice cultivation is applied at that moment. This may partly explain the low nitrogen efficiencies found in European rice.

The economical optimum application level of nitrogen was not established, because the required economical analysis of the variable costs of fertilizer and the variable prices of rice was outside the scope of this study.

In the last chapter, the results of the whole study were related to each other. The presented conclusions may be used in the development of a modern, environment-friendly and competitive rice industry. The minimum losses that may be expected with a relatively low level of fertilizer nitrogen input were estimated. It is shown that relatively high yields can not be realized in Europe, unless current nitrogen recoveries are increased drastically. This awareness should be an incentive for rice-producers to revise their current fertilizer nitrogen strategies.

Samenvatting

Het gebruik van kapitaal-input voor de produktie van voedselgewassen neemt wereldwijd sterk toe. Dit hangt samen met de toenemende vraag naar voedsel en de noodzaak om hogere produkties per landoppervlak te realiseren vanwege de beperkte beschikbaarheid van bouwland. Het stijgend gebruik aan input kan nadelige consequenties hebben voor het milieu en de mens, als daardoor ook de uitstoot van input naar het milieu toeneemt. Verliezen vormen bovendien financiële kosten. Het is dus van belang dat er onderzoek verricht wordt naar een optimaal gebruik van input, zowel in landbouwkundige - als economische zin.

Het beschreven onderzoek heeft zich gericht op de toename van de efficiëntie van stikstof in geïrrigeerde rijst in Europa. Drie indicatoren zijn gebruikt om de stikstof-efficiëntie uit te drukken: i) de toedienings-efficiëntie, die aangeeft welke korrelopbrengst gerealiseerd wordt per eenheid toegediende stikstof (kg kg^{-1}), ii) de gebruiksefficiëntie, ofwel de korrelopbrengst per eenheid opgenomen stikstof (kg kg^{-1}), en iii) de opname-efficiëntie, i.e. de fractie van de toegediende stikstof die door het gewas is opgenomen (kg kg^{-1}). Het onderzoek draagt alternatieven aan om de huidige verspillende bemestingstechnieken in rijst te verbeteren. Een case-studie werd uitgevoerd voor de Camargue in het Zuiden van Frankrijk. Zoals in de meeste Europese rijstbouwgebieden, is daar het gebruik van kapitaal-input per eenheid landoppervlak hoog. Het onderzoek heeft zich gericht op stikstof, omdat dit het meest toegediende voedingselement in de landbouw is en daarom een belangrijke bijdrage kan leveren aan de degradatie van de leefomgeving.

Omdat recente gegevens over de stikstof-efficiëntie in Europese rijstbouw niet voorhanden waren, werden voor de belangrijkste produktiegebieden alle gedefinieerde uitdrukkingen voor efficiëntie gekwantificeerd (Hoofdstuk 2). Allereerst werd een constante waarde van 56 kg kg^{-1} voor de gebruiks-efficiëntie afgeleid, met behulp van uitgevoerde experimenten in 1989 en 1990 in de Camargue. Ook werden waarden voor de toedienings-efficiëntie en de opname-efficiëntie vastgesteld, enerzijds voor een traditionele ureum kunstmest, anderzijds voor gecoate kunstmest (Osmocote-ureum). Deze experimenteel bepaalde stikstof-efficiënties voor normale ureum werden vervolgens vergeleken met die voor de gehele Camargue-regio en met die voor andere Mediterrane produktiegebieden in Europa. Maximale toedienings-efficiënties varieerden tussen de 12 en 17 kg kg^{-1}. Maximale opname-efficiënties bevonden zich tussen de 0.21 en 0.32 kg kg^{-1}. De laatstgenoemde cijfers geven aan dat slechts 21 tot 32% van de toegediende kunstmest-stikstof terug te vinden is in het gewas. Via gebruik van de gecoate kunstmest werd aangetoond dat de toedienings-efficiëntie verbeterd kan worden tot 32 kg kg^{-1} en de opname-efficiëntie tot 0.58 kg kg^{-1}. Deze verbeterde efficiënties kunnen beschouwd worden als streefwaarden voor de nabije toekomst. Helaas is de prijs van gecoate kunstmest relatief hoog, wat een algemeen gebruik niet waarschijnlijk maakt. Daarom werd het vervolgonderzoek gericht op de vraag of de streefwaarden ook behaald konden worden door verbetering van gangbare bemestingstechnieken.

De gegevens van beide Camargue experimenten werden verder geanalyseerd om meer inzicht te verkrijgen op welke wijze stikstofbemestings-strategieën de groei en produktie van rijst beïnvloeden (Hoofdstuk 3). Er werd speciaal aandacht geschonken aan de produktie van het vegetatieve gedeelte van het gewas dat tijdens de korrelvulling de bron vormt van de vulstoffen voor de korrels (de 'source'), en aan de capaciteit van de korrels zich te vullen (de 'sink'). De opnamesnelheid van stikstof en de groeisnelheid van het gewas werden gerelateerd aan verschillende toestandsgrootheden van het gewas door het groeiseizoen. Hieruit bleek dat de dynamiek van de stikstof-opnamesnelheid sterk bepaald wordt door de initiële dichtheid van het gewas. In een dicht gewas wordt de beschikbare bodemstikstof in een relatief korte tijd opgenomen, waarna, bij uitblijven van bemesting, stikstof limiterend voor de groei wordt. Bij een relatief open gewas zal deze limitering later optreden, bij een vergelijkbare initiële hoeveelheid beschikbare bodem-stikstof. Dit houdt in dat bij het ontwikkelen van bemestings-strategieën rekening gehouden moet worden met de actuele toestand van het gewas in combinatie met die van de bodem. Hier wordt in de praktijk te weinig aandacht aan geschonken. Er werd verder aangetoond dat verschillende bemestings-strategieën invloed hadden op de produktie van individuele plantorganen. Er werd geconcludeerd dat met behulp van stikstofbemesting in de vegetatieve groeifase de potentie voor korrelvulling te beïnvloeden is. Een hoge potentiële sourcecapaciteit bleek niet altijd gerelateerd aan hoge korrelopbrengsten. Een van de redenen kan zijn dat bij een gegeven temperatuur het relatieve aandeel van ademhalingsverliezen in de totale carbohydraten-balans van het gewas toeneemt met de hoeveelheid aanwezige biomassa. Ondanks een hoge sourcecapaciteit kan er dan toch sprake zijn van source-gelimiteerde korrelopbrengsten. Om de risico's van oogstderving te beperken, werd geadviseerd om te streven naar een gewas dat rond de bloei een gematigd bladoppervlak heeft met een hoog stikstofgehalte. Verder systeemanalytisch onderzoek is nodig om voor verschillende produktiegebieden, produktiejaren, en variëteiten, deze richtlijnen kwantitatief te maken.

Een simpel gewas-groeimodel werd ontwikkeld om de stikstofgelimiteerde produktie van rijst te simuleren (Hoofdstuk 4), en vervolgens het effect van alternatieve bemestingsstrategieën op de gewasproduktie en de stikstofopname-efficiëntie te kunnen kwantificeren (Hoofdstuk 5). Tot slot werd een stikstofbemestingsadvies gegeven dat toegesneden was op de veel gebruikte variëteit 'Lido' in de Camargue. Er werd gevonden dat kunstmest N toegediend gedurende de exponentiële- en lineair groeifasen van het gewas, het meest effectief voor de produktie was. Bij hoger niveaus van N toediening, bleek een extra bemesting rond de bloei het meest effectief. Dit advies combineert een maximaal haalbare opname-efficiëntie met hoge gewasproduktie. Simulatie toonde aan dat onder de actuele produktieomstandigheden in de Camargue een korrelopbrengst van 8.4 Mg ha^{-1} maximaal haalbaar is voor Lido. In werkelijkheid zal deze opbrengst moeilijk realiseerbaar zijn, omdat in deze berekening werd aangenomen dat stikstof continue aan het gewas werd aangeboden. In de praktijk wordt stikstof op discrete momenten in het groeiseizoen toegediend. Optimalisatie van de bemestingsstrategie is dan alleen mogelijk door aanpassing van dosering en tijdstip van toediening.

Om tot een gefundeerd bemestingsadvies te komen, werden 70 bemestings-strategieën doorgerekend voor 20 seizoenen. Per niveau aan totaal toegediende stikstof werden totale produktie en opname-efficiëntie per strategie gekwantificeerd. Hoge opname-efficiënties en hoge gewasopbrengsten werden verkregen bij toediening van stikstof bij het begin van de uitstoelingsfase en bij pluiminitiatie. De opname-efficiëntie bleek te kunnen stijgen van 0.21 tot 0.51; meer dan een verdubbeling van de stikstofopname uit kunstmest. De gemiddelde gewasprodukties over 20 jaar bleven niet achter op die uit de Camargue experimenten. De gewasproduktie nam toe met de hoeveelheid toegediende stikstof, maar de opname-efficiëntie nam dan sterk af. Bij totale doseringen van meer dan 150 kg ha^{-1} aan stikstof werd berekend dat deze hoeveelheid het meest efficiënt in drie fracties kon worden toegediend: aan het begin van uitstoeling, bij pluim-initiatie, en aan het begin van de bloei. Omdat de actuele stikstofgiften aan Europese rijst ruim boven de 150 kg ha^{-1} uitkomen, en omdat een toediening rond bloei niet gangbaar is in de Camargue, is het gewenst om via experimenten de merites van de derde stikstofgift rond bloei te onderzoeken. Simulatie geeft verder aan dat opname-efficiëntie van stikstof toegediend vòòr de inzaai van het gewas zeer laag is, terwijl in de Europese rijstbouw de meeste stikstof juist op dat moment wordt toegediend. Dit kan ten dele de lage stikstof-efficiënties in de Europese rijstbouw verklaren.

Het economisch optimale stikstof-bemestingsniveau werd niet vastgesteld, omdat de hiervoor benodigde analyse van de variabele kosten van stikstofmeststof en de variabele prijs van rijst buiten het kader van de studie valt.

In het laatste hoofdstuk (Hoofdstuk 6) werden de resultaten van het gehele onderzoek met elkaar in verband gebracht. De gepresenteerde conclusies kunnen gebruikt worden om een moderne, milieu-ontziende en concurrerende rijstbouw in Europa te ontwikkelen. Schattingen zijn gegeven over de minimale stikstofverliezen die verwacht mogen worden bij een lage input aan stikstof. Er wordt aangetoond dat het behalen van relatief hoge rijstopbrengsten in Europa uitgesloten moet worden, tenzij de huidige lage stikstof opname-efficiënties drastisch worden verbeterd. Deze wetenschap zou voor rijstproducenten een reden moeten zijn om hun huidige bemestingsstrategieën te herzien.

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Curriculum vitae

Nicolaas Charles Stutterheim was born March 3, 1958, in 's Gravenhage, The Netherlands. He started his study in agronomy at the Wageningen Agricultural University, The Netherlands in September 1980. From July 1985 till January 1986 he worked as a research student at Griffith University in Brisbane, Australia, on the turnover of carbon and nitrogen in the soil microbial biomass. In January 1988 he graduated from the Wageningen Agricultural University with specializations in soil chemistry and soil fertility, agronomy and production ecology. The first two years following his study, he worked at the 'Institute National de la Recherche Agronomique' (INRA) in Montpellier, France, on nitrogen dynamics in fully irrigated rice soils. From 1990 till 1994 he was employed by the research institute for AgroBiology and soil fertility (AB-DLO) in Wageningen. This period was used to accomplish this thesis. Since March 1995, he is employed by the 'Centre de Coopération Internationale en Recherche Agronomique pour le Développement' (CIRAD) in Montpellier, France, to quantify the effects of different availability of nutrients and water for several *gramineae* crops cultivated under semi-arid conditions.